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PRELIMINARY RESULTS OF MEASUREMENTS OF THE RIGIDITY OF THE EARTH

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Measurements of the temperature of the crust of the earth as found in the deepest mines show that it rises on the average about 0.02° C. for every meter below the surface; and as the rate of increase is even greater at greater depths it follows, as Lord Kelvin pointed out,[1] that the temperature in the interior must be high enough to melt the substances composing it, and for a long time it was considered that the vast bulk of the earth must be in a fluid, or at least semi-fluid, condition, a conclusion which was strongly supported by the fact of the ejection of molten lava from volcanoes.

The theoretical investigations of Lord Kelvin in 1863[2] indicated, however, that the earth must be considered a very rigid body, opposing an enormous resistance to changes of form such as tend to occur in consequence of the attractions of the sun and moon. It is evident from these investigations that the old idea (which is not entirely extinct) that we are living on a thin rock crust over an immense mass of molten lava must be abandoned.

[1] *Philosophical Transactions*, 1863. [2] *Ibid.*

The first attempt to measure the rigidity of the earth, that is, the resistance which it offers to change of shape, was made by G. H. and Horace Darwin in 1880.[1] They employed a horizontal pendulum by the use of which they hoped to measure the change in the direction of the gravitational vertical due to the attractions of the sun and moon; from which, by comparison with the values calculated on the basis of absolute rigidity, the effective rigidity could be determined. The results were so irregular and contradictory that no conclusion could be formed, and the Darwins express the belief that such experiments are not likely ever to furnish the desired results.

In the hands of Rebeur-Paschwitz this method did, however, give positive results confirming the deductions of Kelvin. Since then the method of the horizontal pendulum has been successfully employed by Ehlert, Kortazzi, Schweydar, Hecker, and Orloff, with essentially the same result, namely, that the coefficient of rigidity is found to be of the order 6×10^{11} c.g.s. (about the same as that of steel). The results deduced from Chandler's observations of the variation of the latitude give a value nearly twice as great.

But, in addition to the elastic yielding of any body ordinarily looked upon as solid there is a plastic yielding, characterized by a constant termed by Maxwell the "modulus of relaxation," and evidenced by a lag of the distortion of the earth relative to the forces producing it. Such experiments as these should be capable of determining the plasticity as well as the rigidity of the earth. To show what measure of reliability may be accorded to the observations mentioned, the following extract, Table I, is made of a discussion of these by Schweydar.[2]

Here $1-K$ represents the ratio of the observed amplitude of oscillation to that calculated on the assumption of absolute rigidity. κ represents the retardation (which should always be negative) of the phase of the observed motion relative to the phase of the disturbing forces.

[1] *B.A.A.S. Reports*, York meeting, 1880.

[2] Dr. Wilhelm Schweydar, *Untersuchungen über die Gezeiten der Festen Erde*. Potsdam, 1912; Leipzig: B. G. Teubner.

The observations are divided into two classes, the latter being considerably more reliable than the former.

TABLE I

Experimenter		K	κ
v. Rebeur		0.362	$+ 7°30'$
Kortazzi		.608	0
"		.414	$- 2°54'$
Ehlert		.448	$+12° 1'$
Schweydar		.338	$- 8°31'$
"		.158	$+ 8°29'$
N.-S.	Hecker	.643	$-11°9$
	"	.565	$- 0°7$
	"	.544	$+13°4$
	Orloff	.412	$+ 0°8$
E.-W.	Hecker	.259	$- 7°0$
	"	.382	$+ 5°2$
	"	.468	$+20°1$
	Orloff	0.326	$+ 3°2$

While the numbers in the second column agree in showing that the earth's rigidity is of the order of that of steel, the differences are so considerable that it is hardly likely that they can be relied upon to within 20 per cent.

If accurate, the third column would give a measure of the plastic yielding of the body of the earth to the action of the distorting forces of the sun and moon. As mentioned before, these should all be negative, whereas the great preponderance is in the direction of positive lag, which is meaningless; so that further than showing that the lag is small (and therefore the viscosity high) these results are practically valueless.

It will be conceded that there is great need for more accurate determinations, if our knowledge of the properties of the matter constituting the earth's interior is to be increased; and it was in the hope of obtaining results of a higher order of accuracy, as well as such directness and simplicity of apparatus as practically to eliminate all the difficulties and uncertainties which seem to be unavoidable in the use of the horizontal pendulum, that the experiments recorded here were undertaken.

The prime object of the investigation is the determination of the direction of the gravitational vertical, or rather of the changes

to which it is subject in consequence of the attraction of the sun and moon and as modified by the resulting distortion of the body of the earth. But this may be furnished with any desired degree of accuracy by the changes in the position of the level of a liquid surface which is necessarily normal to the resultant of all the forces acting. If from these we can eliminate all but the gravitational forces the problem is solved.

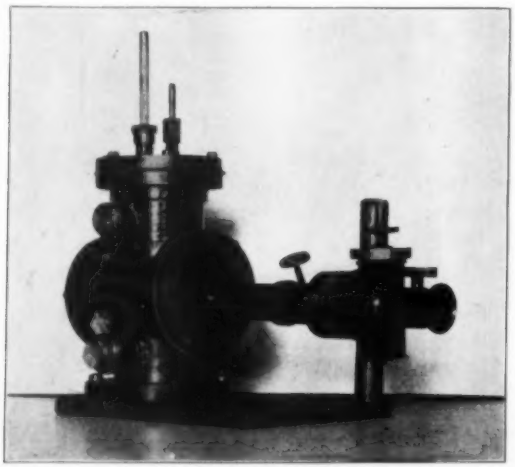

FIG. 1.—Microscope and gauge

A very sensitive method of measuring the changes in level is furnished by the interferometer; and a method of carrying this into practice was devised and the apparatus constructed[1] in 1910.

But before attempting to utilize so delicate an appliance it was deemed advisable to make these preliminary experiments with the microscope. Accordingly a 6-inch pipe, 500 feet long, was half filled with water,[2] the level of which could be read off through the glass sides of the end vessels, as shown in Fig. 1.

[1] An interference apparatus for this purpose was independently devised by Professor A. G. Webster.

[2] The vessels at the ends were at first connected by a pipe filled with water, but with this arrangement temperature changes produced enormous disturbances in the level.

This pipe was laid in a trench six feet deep, terminating in two pits, eight feet square and ten feet deep, walled with concrete, in a soil of sandy clay on the grounds of the Yerkes Observatory at Williams Bay, Wisconsin. The direction (E.–W.) of the pipe was laid out by measuring from the meridian line and is probably correct to within one foot in five hundred. The pipe was then carefully leveled, and after verifying the continuity of the water and

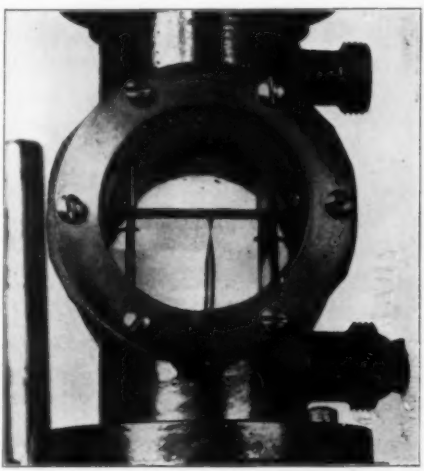

FIG. 2.—Point and totally reflected image

of the air space above it, the pipe was closed so that it was effectively air-tight, and the trench was filled with clay.

The distance between the total reflection image of a pointer, Fig. 2, and the direct image was read by micrometer microscopes of about 2-inch focus. These were calibrated at first rather roughly by measuring the diameter of a wire immersed in the water at the focus; and subsequently with much greater accuracy by measuring the known distance between two lines ruled on glass and placed in the focus, under water.

A preliminary series of observations was begun August 5 and continued until September 2 with such encouraging results that it

was decided to supplement the work by observing on a N.–S. line which was accordingly laid out in the same manner as the E.–W. line.

The final calibration of the microscopes gave the following results:

West	17.52	turns	= 1 mm
East	17.60	"	= 1 mm
North	17.00	"	= 1 mm
South	17.60	"	= 1 mm

The mean for the E.–W. line is 17.56, and for the N.–S. line, 17.30. Accordingly the factor by which the calculated difference in level in mm should be multiplied to reduce to micrometer divisions is

For the E.–W. line, 285
For the N.–S. line, 289

The factor actually used in the computation was 293, and accordingly these should be diminished by 2.8 per cent for the E.–W. line, and by 1.4 per cent for the N.–S. line.

A continuous series of observations was conducted on both lines, beginning September 27 and ending November 29. The observations were made by setting the cross-hair of the micrometer on the pointer and taking a number of readings, the mean of which gave the fiducial reading to be subtracted from the readings of the reflected image. This difference was subtracted from a similar difference taken at the other end of the pipe, and the final differences from hour to hour (plus a constant) gave the observed curves. These readings were taken every hour from 6 A.M. until midnight, and every two hours from midnight until 6 A.M. The order of the observations was usually south end, north end, east end, west end. The time between readings at south end and north end, or between east end and west end, was about four minutes, and the mean between the two was taken to represent the time of observation. The mean time of the two observations gives the same result as though the observations had been simultaneous.

Occasionally the reflected image would be obscured by floating particles, and in clearing these away the value of the constant would be altered. The new constant was accordingly chosen so that the succeeding observations continued with the smallest discontinuity in the curve.

It was found that there was a gradual downward trend in the E.–W. curve during August, but little or none in the October-November series. The N.–S. line, however, on which readings were started the day after the pipe was covered, shows a considerable gradual drop. This was undoubtedly caused by uneven settling at the ends of the pipes. This was too slow to affect the result for the semi-diurnal period, but made doubtful the results for the fortnightly period.

The observations and their graphs are given in Tables III and IV and in Figs. 3 and 4.

In Figs. 5 to 12 these graphs are reproduced on a larger scale, together with those of the calculated values of the readings, multiplied by the factor 0.7 for the E.–W. line and 0.5 for the N.–S. line. The zero line of the observed readings is corrected to coincide with the calculated curve.

These curves were divided into periods corresponding to the semi-diurnal lunar tide, 12.42 hours, and the values at corresponding intervals of two hours tabulated and divided into groups of ten periods each.

The results of the comparison of the observed and calculated curves is given in Table II, in which the first column gives the ratio of the observed amplitudes to the calculated, on the assumption of an absolutely rigid earth, and the second the retardation of phase in hours.

TABLE II

Ratio of Amplitudes		Retardation in Phase	
E.–W.	N.–S.	E.–W.	N.–S.
0.69	0.50	-0^h05	-0^h06
.79	.54	+ .30	+ .30
.65	.53	− .14	− .08
.71	.50	− .01	− .03
.82	.53	− .08	+ .12
.64	.52	− .14	− .20
.66	.50	− .08	.00
.70	.50	− .03	.00
.70	.50	− .12	− .06
.74	.50	− .16	− .02
.70	.48	− .12	+ .08
0.71	0.52	−0.08	+0.04
Mean = 0.709 × 1.028	0.510 × 1.014	−0.059	+0.0075

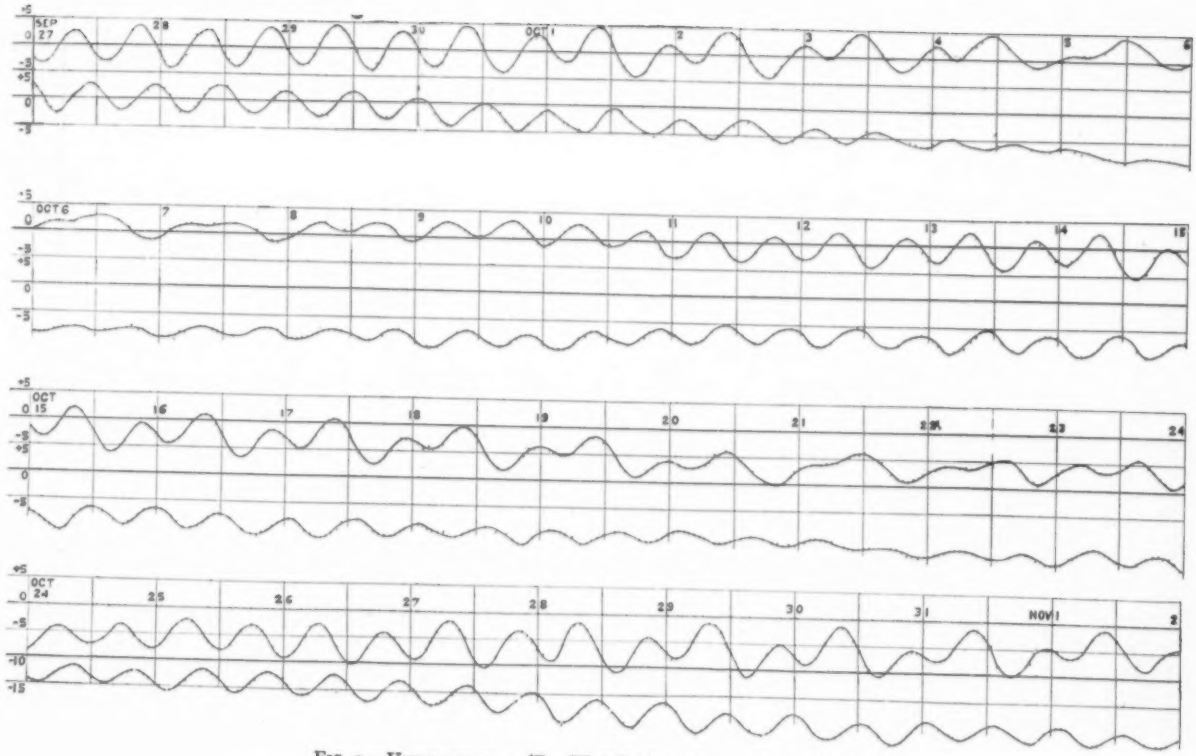

FIG. 3.—Upper curves, 10(E.−W.+C); lower curves, 10(S.−N.+C)

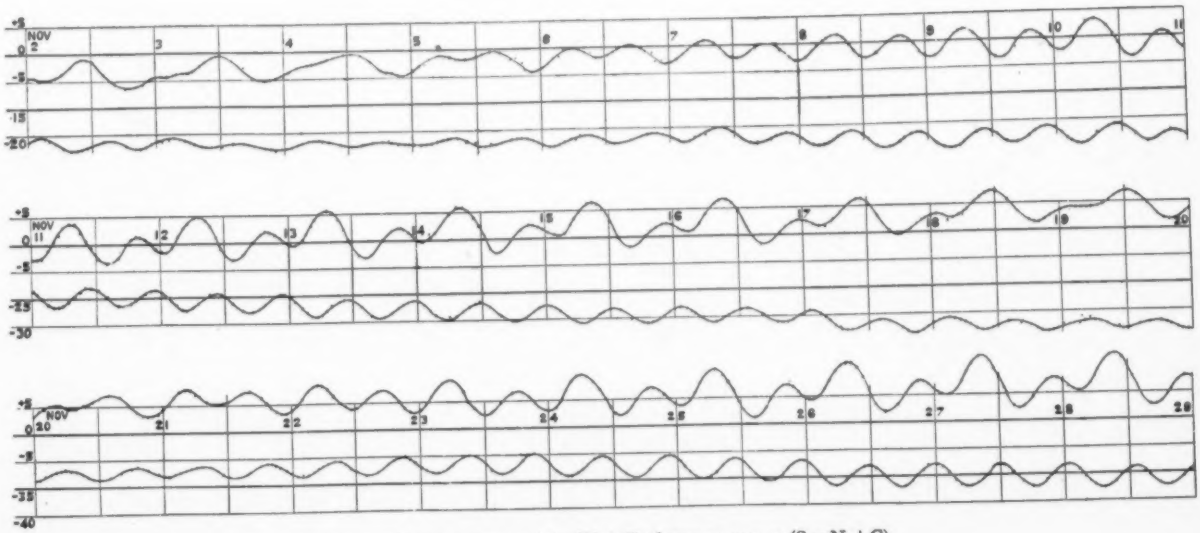

FIG. 4.—Upper curves, 10(E.−W.+C); lower curves, 10(S.−N.+C)

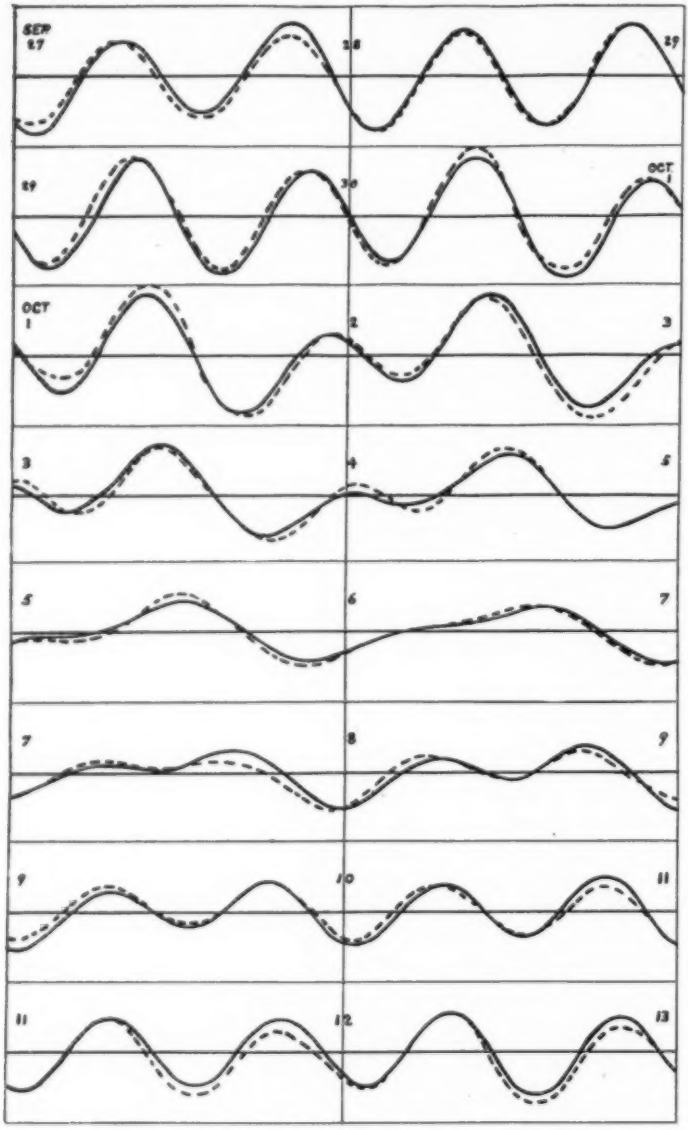

FIG. 5.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

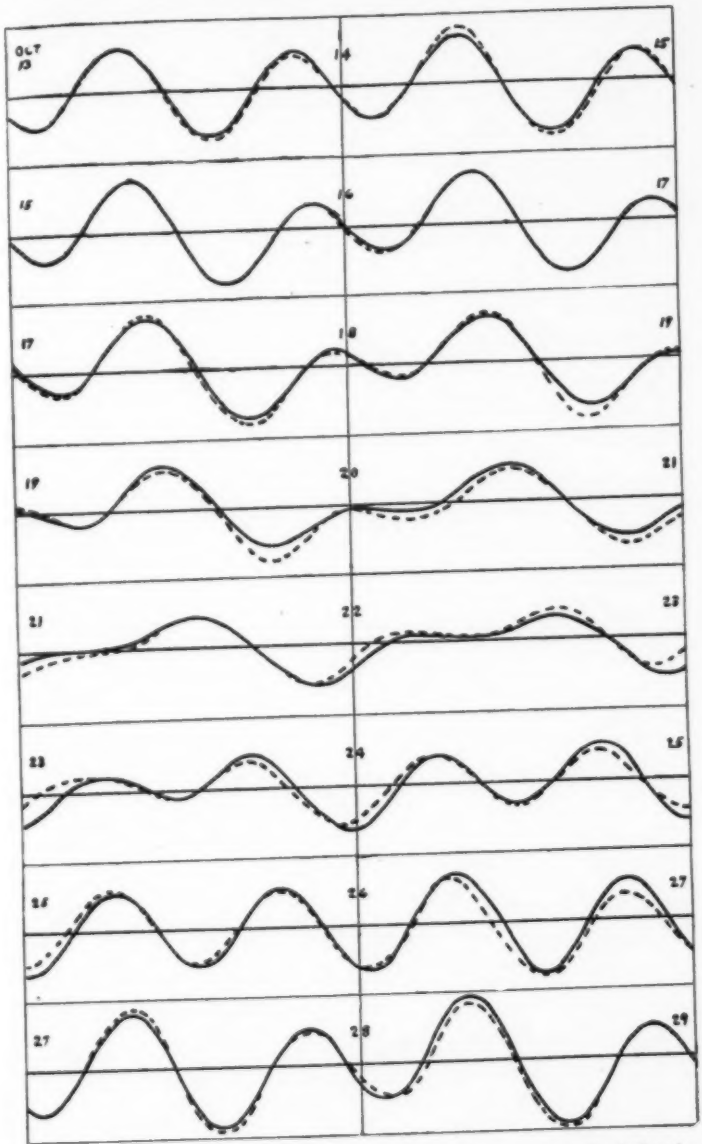

FIG. 6.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

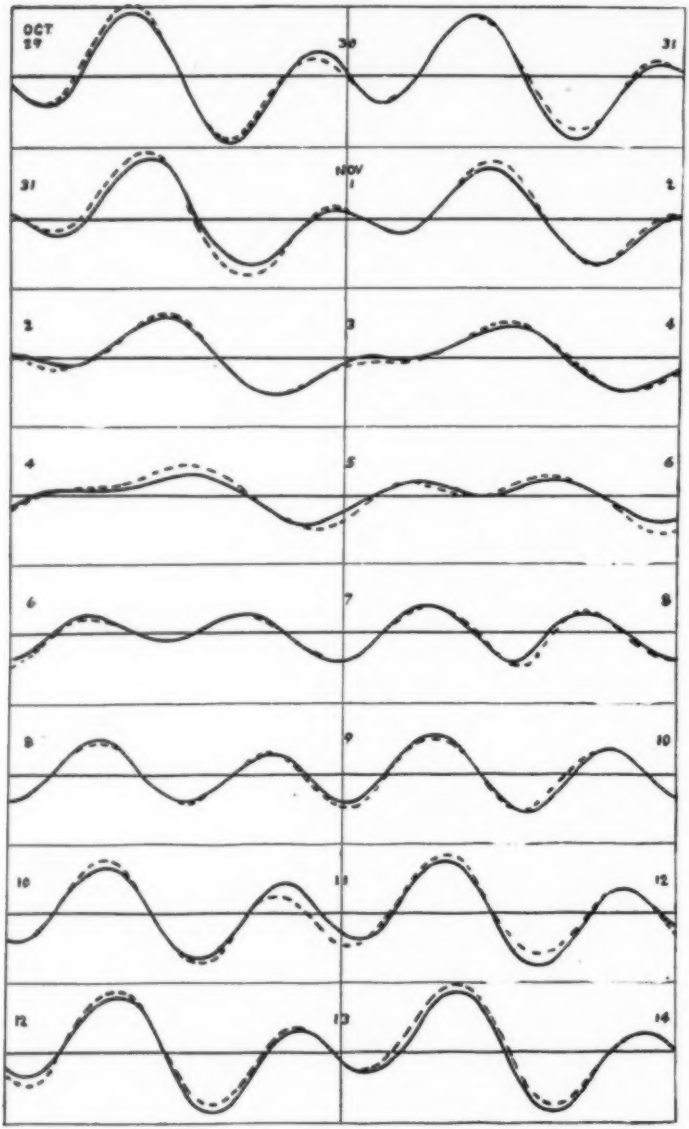

FIG. 7.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

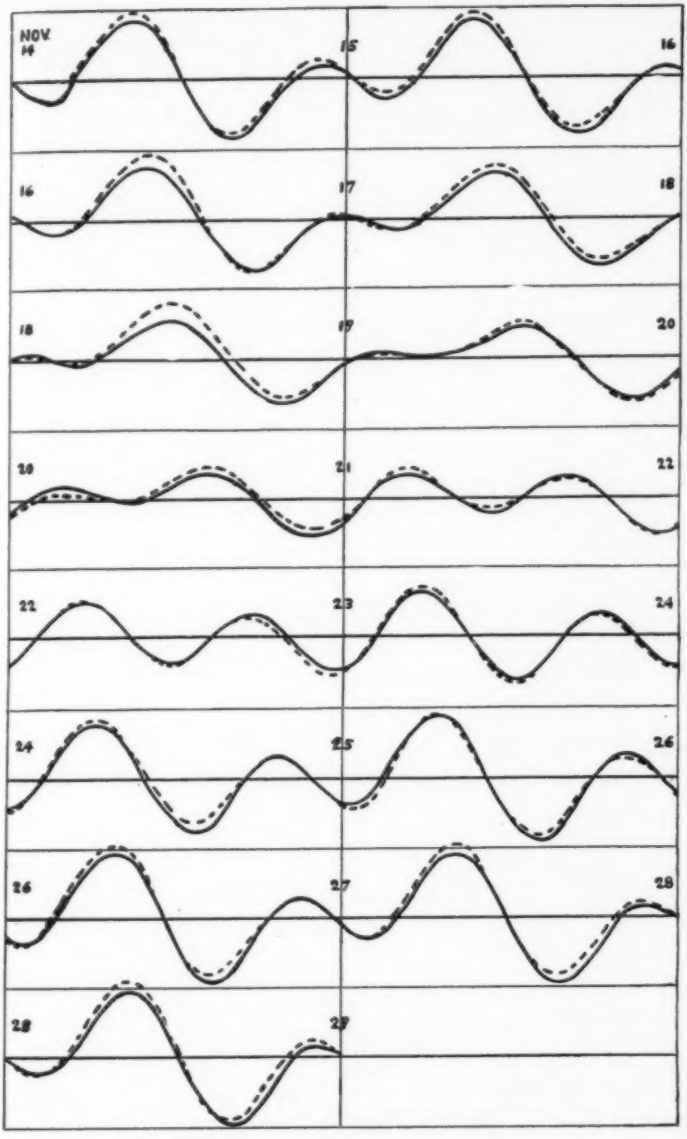

FIG. 8.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

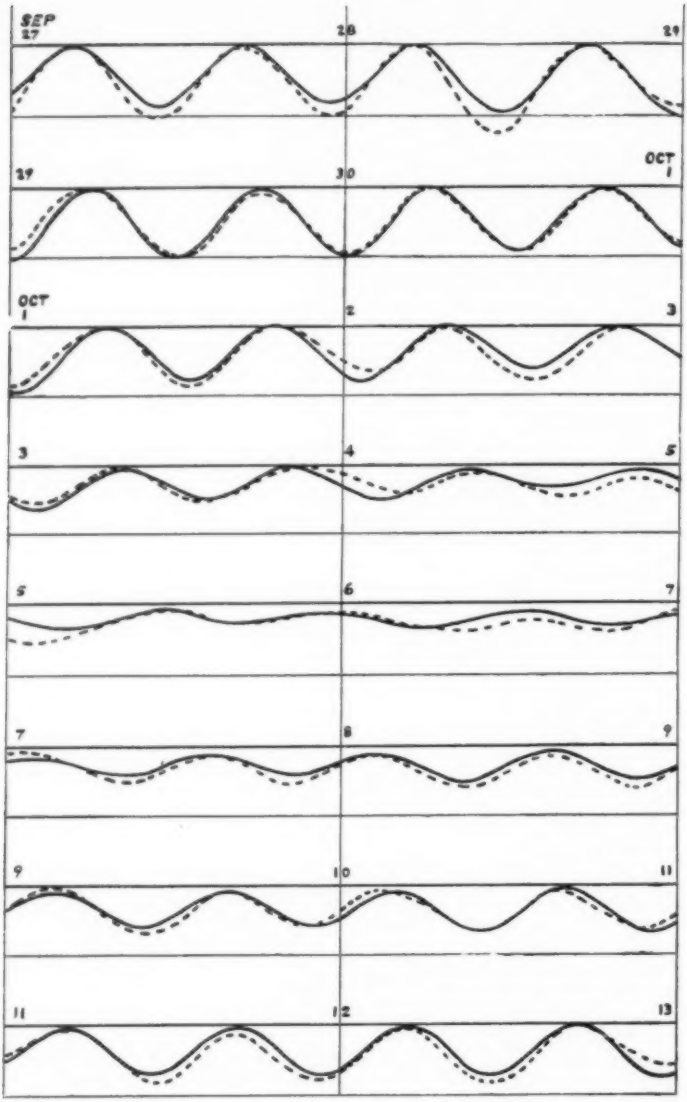

FIG. 9.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

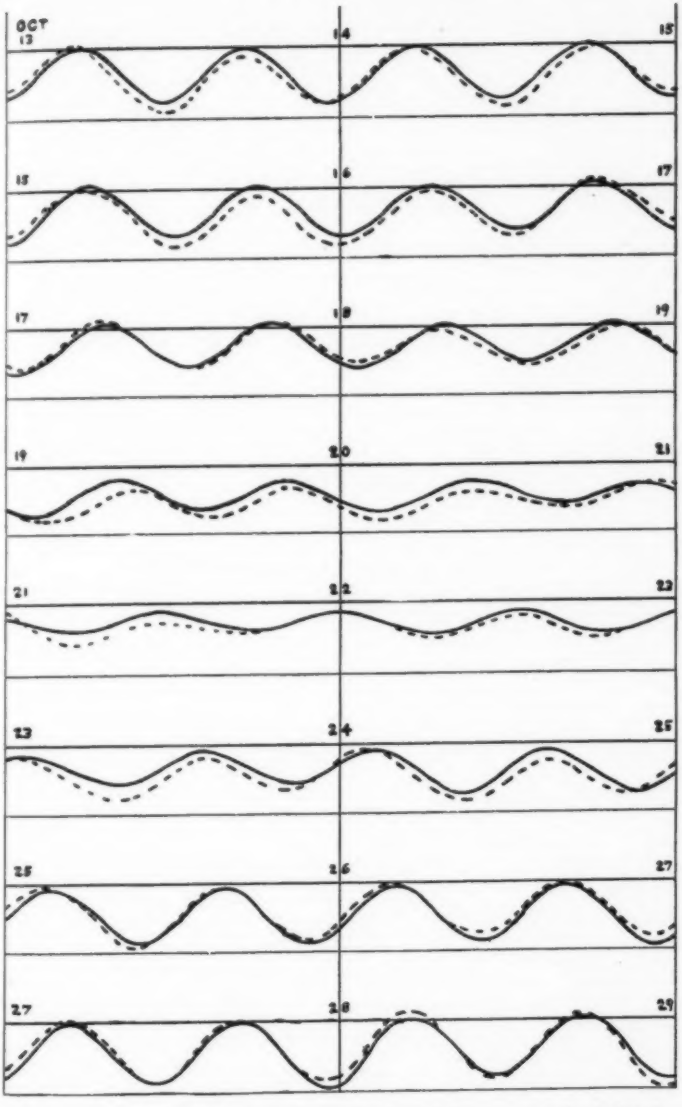

FIG. 10.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

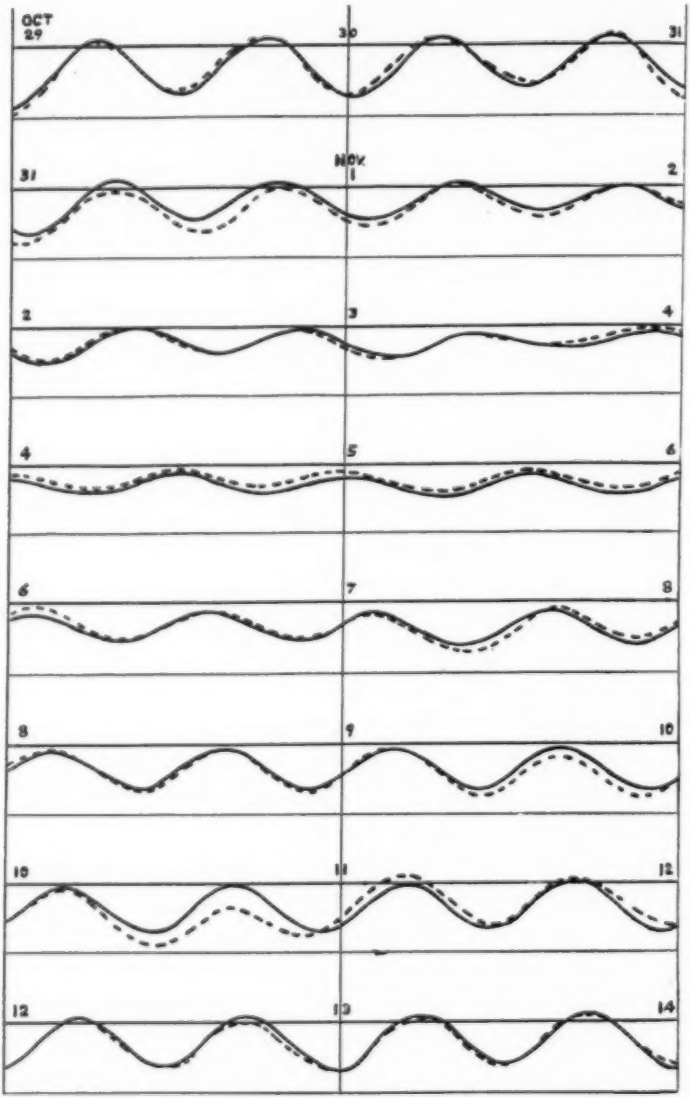

FIG. 11.—N.–S. Dotted curve, observed values; full curve, 0.5 of calculated

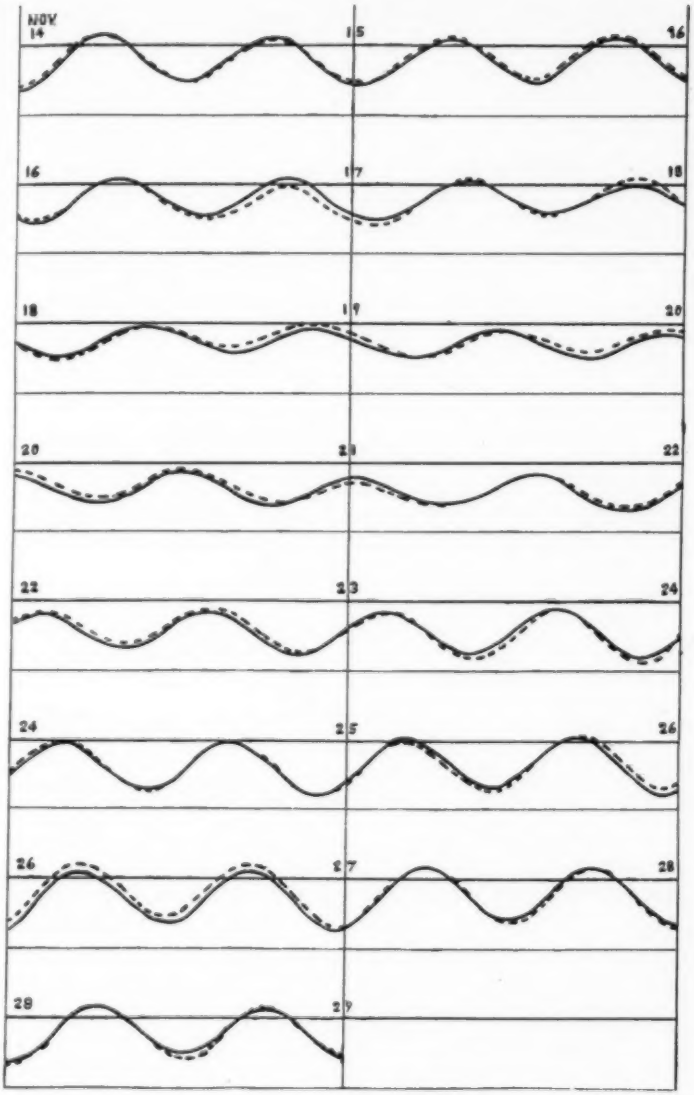

FIG. 12.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

The resulting mean of all observations, for this method of grouping, is that the observed amplitude of the oscillation for the E.–W. line is 0.709 of that calculated on the assumption of absolute rigidity; while for the N.–S. line it is 0.510. The acceleration of phase of the observed oscillations relative to the calculated is $+0^h.059$ for the E.–W. line and $-0^h.007$ for the N.–S. line. The graphs of the final means of all the observations and the calculated values are reproduced in Figs. 13 and 14.

The curves correspond very closely with the following formulae:

$$\text{E.–W.} \quad y = -a \sin \frac{2\pi}{T}(t-\tau)+b$$

$$\text{N.–S.} \quad y = -a \cos \frac{2\pi}{T}(t-\tau)+b$$

with the following values for the constants:

E.–W.

Calculated × 0.7	Observed
$a = 20.56$	$a = 20.30$
$\tau = 0.99$	$\tau = 0.88$
$b = 0.33$	$b = 0.30$

N.–S.

Calculated × 0.5	Observed
$a = 13.18$	$a = 13.60$
$\tau = 0.99$	$\tau = 0.97$
$b = 0.16$	$b = 0.13$

Accordingly the ratio of the observed to the calculated amplitude for E.–W. is 0.691, and for N.–S. is 0.516, while the phase accelerations are $0^h.11$ and $0^h.02$ respectively.

These last results are slightly different from the preceding. The preference is for the latter as regards amplitude ratios, but these give relatively too much weight to the large oscillations in deducing the phase-difference, and for these the former results are preferred.

Multiplying the second set of values obtained for the amplitude ratios by the factors given above, 1.028 for E.–W. and 1.014 for N.–S., the final results are:

Amplitude Ratio	Phase Acceleration
E.–W. 0.710	**E.–W. ..... +0.059 hour**
N.–S. 0.523	**N.–S. ..... −0.007 hour**

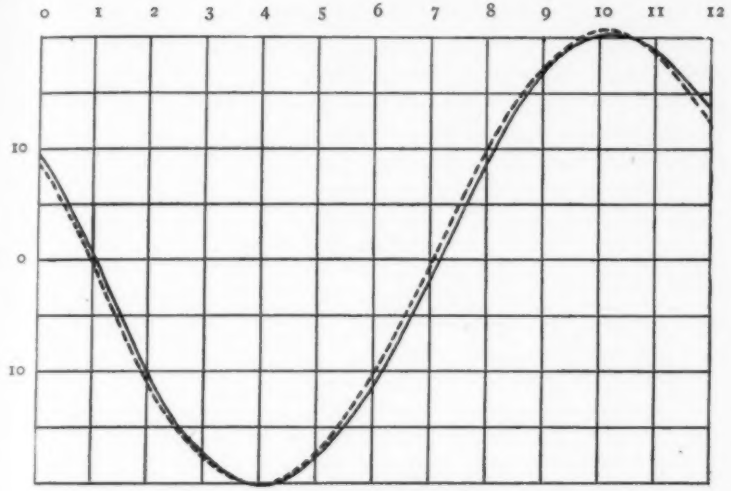

FIG. 13.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

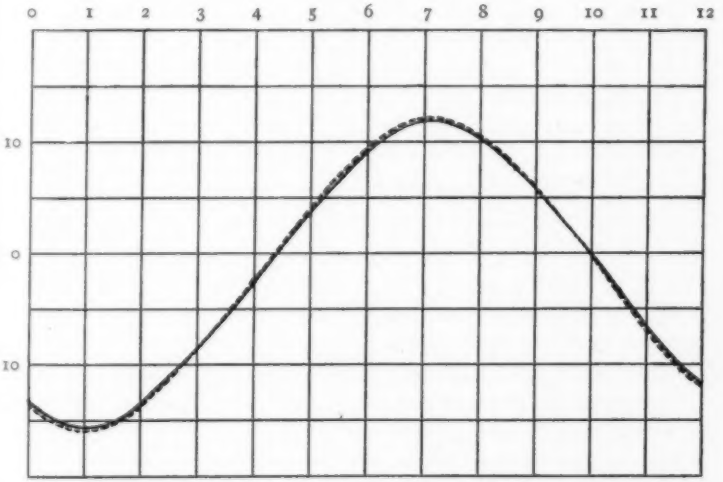

FIG. 14.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

It is estimated that the errors in the amplitude ratios are under 1 per cent. The phase acceleration is probably correct to within $0^h.03$, but is so small as to leave some doubt as to whether or not it is real.

The disagreement between the E.–W. and N.–S. directions has been interpreted by Hecker, who found a similar difference, as

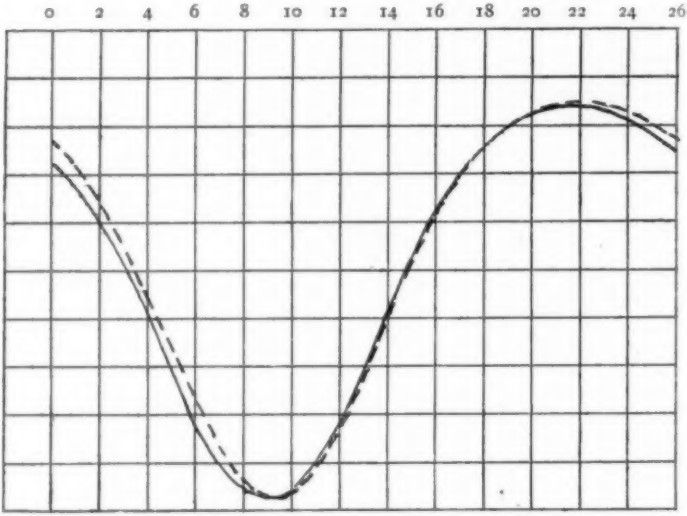

FIG. 15.—E.–W. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

indicating an actual difference in the earth's rigidity in the E.–W. and N.–S. directions.

Schweydar agrees with A. E. H. Love in attributing the difference to the effect of ocean tides, and shows on the assumption of an ocean covering the earth uniformly to a depth of 5000 meters that the tides have the effect of increasing the elastic earth tides, so that the ratio of the observed amplitudes to the theoretical is diminished by something like 40 per cent.

The mean values of the ratio adopted by Schweydar are 0.61 for E.–W. and 0.46 for N.–S., which should therefore be increased

to 0.85 and 0.64 respectively. A similar correction applied to the results of these experiments would give, instead of 0.71 and 0.52, the values 0.99 and 0.73. The E.–W. value would mean that the earth's rigidity is practically infinite, and it is undoubtedly too high.

The ocean is, however, anything but uniform in depth, and this and the irregularities in coast lines, make an accurate calculation of the disturbing effect of the ocean tides almost impossible. Accordingly Schweydar, considering that the results furnished by

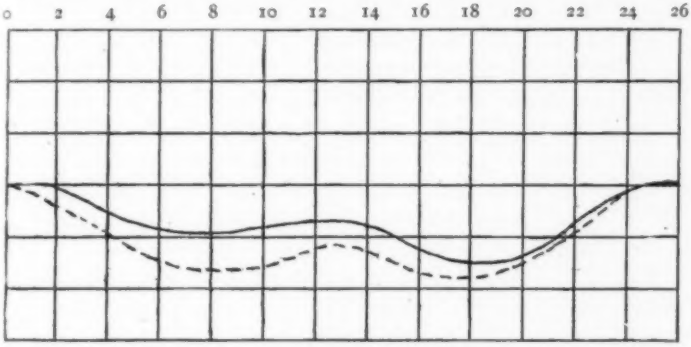

FIG. 16.—N.–S. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

the consideration of the semi-diurnal tides is not reliable, investigated the problem of the diurnal period, especially that corresponding to the "declination tide" whose period is 25^h812. The dynamical theory shows that for an ocean entirely covering the earth, such tides should vanish; a result which is approximately true, at least for the Atlantic.

This analysis applied to Hecker's observations gives 0.85, as the value of the ratio, which, it will be noticed, agrees with the value for the semi-diurnal period when corrected for the calculated perturbation of the ocean tides.

The result of grouping the present observations into six groups of two periods each (of 25^h81) is reproduced in the graphs of Figs. 15 and 16.

These were analyzed by means of the harmonic analyzer, and

gave the following results, in which R is the ratio of the observed amplitude to the calculated, and ϕ the phase acceleration:

	R	ϕ
E.–W.....	0.72	−0.4 hour.
N.–S.....	0.66	+1.0 "

It appears therefore that the diurnal period gives for the amplitude ratios numbers which are decidedly in better agreement than those furnished by the semi-diurnal period.

It is to be noted that while the agreement between the E.–W. and the N.–S. results is considerably improved, the value of R for the E.–W. direction has not been altered, whereas according to Schweydar's investigation it should have been much larger (0.90 or more). It may be, however, that first, in consequence of the smaller number of periods entering the calculation, and secondly, on account of the smaller value of the resulting amplitude (41:100), these numbers have a considerably larger probable error than that of the semi-diurnal period.

Possibly a closer analysis of the actual ocean tides would show that the effect is small for the E.–W. direction, while in the N.–S. direction it may be considerable.

Regarding the acceleration of phase, it may be noted that the difference between the E.–W. and the N.–S. direction is much greater for the diurnal period than for the semi-diurnal, whereas, if the results of the latter were seriously affected by the ocean tides, the reverse should hold. The mean of the semi-diurnal accelerations is $0^h.03$, a quantity so small that it is within the probable error. Taking this value together with 0.70 as the ratio of the observed to the calculated amplitudes, the corresponding values of the earth's rigidity n and viscosity ϵ are:

$$n = 8.6 \times 10^{11} \text{ c.g.s.}$$
$$\epsilon = 10.9 \times 10^{16} \text{ c.g.s.}$$

This calculation is based on the assumption of uniform rigidity throughout the body of the earth, a condition which is certainly not fulfilled; and that as the time increases in arithmetical progression the stresses diminish in geometrical progression. It is clear, however, that the earth's rigidity is greater than that of steel. If the

ocean tides have the effect of diminishing the ratio R by from $\frac{1}{2}$ to $\frac{1}{3}$, as admitted by Schweydar, the rigidity is enormously greater.

The viscosity is also very great and probably of the same order of magnitude as that of steel.

The main object of this investigation was to demonstrate the feasibility of the method and to determine the order of magnitude of the earth's rigidity and viscosity. Evidently the method is capable of giving results of a high order of accuracy by recording a much longer series of observations. Such a series, in which the microscope will be replaced by the interferometer and in which the record is to be made automatic, is now in preparation. It is expected that the results will furnish a record of the earth tides which will be correct to within a tenth of 1 per cent.

Whether it may thereby be possible to obtain a more accurate value of the coefficients of rigidity and of viscosity will depend on the advance which may be made in the theory of the ocean tides and of their perturbing action. Doubtless it would be of importance to repeat the experiments at widely different stations, some in the southern hemisphere, some on islands in mid-ocean, and some on the continent as far as possible from the coast.

It may also be possible by a comparison of the moon and the sun tides to obtain an independent and perhaps more accurate value of the moon's mass.[1]

The conclusions from these and similar experiments and observations, including precession and variation of latitude, all agree substantially in refuting the old notion that the internal temperature, sufficiently high to melt most of the materials constituting the earth's crust, necessarily involves a fluid or semi-fluid earth supporting a relatively thin solid crust.

From the definitely ascertained result that the coefficient of rigidity and the coefficient of viscosity are both very large (of the order of, and perhaps exceeding, those of solid steel, whereas under normal pressure all substances at this temperature would be fluid), it follows that pressure increases the rigidity and the viscosity, at least of the substances which form the body of the earth.

[1] It would probably be necessary to make use of a tunnel sufficiently deep to eliminate the thermal effect, which even in the semi-diurnal period would be appreciable.

It would be interesting to confirm this important conclusion, even qualitatively, by experiments on the effect of such relatively small pressures as we are able to obtain in the laboratory.

Such experiments are now in progress; and while the highest pressures obtainable are a thousand times smaller than the pressure in the interior of the earth, it may be stated that there are distinct indications of an increase in the coefficient of rigidity, and a marked increase in the coefficient of viscosity of the few materials thus far investigated.

I would take this opportunity of expressing my appreciation of the interest taken in this work by Professor T. C. Chamberlin, at whose instigation the investigation was undertaken, and of tendering thanks to him and to President H. P. Judson for their efforts in securing the necessary funds. I would also gratefully acknowledge the friendly co-operation of Professor Frost and the members of the staff of the Yerkes Observatory.

TABLE III 10(E.−W.+C.)

A.M. September 27	A.M. September 30	P.M. October 2	A.M. October 5	A.M. October 8
C=+1.30	12:12 − 0.6	4:10 − 1.3	11:32 ± 0.0	6:29 + 0.7
	2:12 − 3.6	5:08 − 1.0	1:02 + 0.9	7:03 + 0.2
8:16 + 1.6	3:12 − 4.1	6:08 + 0.7	2:46 + 1.0	8:08 − 0.9
9:11 + 0.7	4:14 − 2.8	7:14 + 1.8	4:04 + 1.1	9:06 − 1.0
10:12 − 0.8	5:12 − 1.3	8:11 + 3.4	5:17 + 0.9	10:22 − 1.5
11:16 − 2.4	6:18 + 0.6	9:09 + 3.9	6:07 + 1.2	11:14 − 0.8
11:56 − 2.7	7:18 + 2.3	10:31 + 4.2	8:08 + 1.9	12:14 − 0.5
1:10 − 3.3	8:20 + 3.1	11:30 + 3.0	9:22 + 2.9	1:08 − 0.3
2:10 − 3.2	9:56 + 3.0	12:30 + 2.0	10:27 + 3.9	2:08 + 0.4
3:15 − 2.1	11.02 + 1.5	2:02 − 1.2	12:06 + 4.4	3:10 + 0.8
4:06 − 0.1	12:04 − 0.3	3:18 − 2.6	2:24 + 3.6	4:06 + 1.7
5:14 + 0.6	1:12 − 2.3	4:14 − 3.6	4:11 + 2.1	5:09 + 2.1
5:48 + 1.8	2:20 − 3.1	6:40 − 3.3	6:31 ± 0.0	5:53 + 2.2
7:08 + 2.5	3:20 − 3.0	7:58 − 1.8	8:34 − 1.1	7:05 + 2.7
8:16 + 2.5	4:14 − 2.2	9:10 ± 0.0	9:18 − 0.8	8:06 + 1.7
9:19 + 1.2	5:10 − 0.8	10:20 + 1.0	C= +3.00	9:22 + 1.1
10:26 − 0.4	5:52 + 0.8	11:10 + 1.5		10:35 + 1.1
11:12 − 1.8	7:11 + 3.4	12:06 + 2.2	10:18 − 0.7	12:23 + 0.8
12:14 − 2.8	7:53 + 4.2	1:18 + 1.8	11:22 − 0.1	1:54 + 1.7
2.04 − 2.9	10:32 + 3.3	2:14 + 1.1	12:15 + 0.3	4:19 + 2.4
4:04 − 0.8	1:46 − 3.0	3:14 + 0.2	1:23 + 0.9	6:10 + 2.5
6:09 + 2.8	3:31 − 3.9	4:15 − 0.2	2:16 + 1.2	7:10 + 1.9
9:30 + 1.8	4:21 − 3.7	5:06 − 0.2	3:18 + 1.6	8:02 + 1.2
10:26 + 0.4	5:28 − 2.6	5:45 + 0.2	4:24 + 1.7	9:12 + 0.1
11:15 − 1.1	6:30 − 0.8	7:09 + 1.7	5:02 + 1.7	10:06 − 0.5
12:22 − 3.0	8:39 + 2.4	8:22 + 3.1	5:54 + 1.9	11:12 − 0.9
1:17 − 4.1	9:48 + 2.7	9:48 + 4.2	7:04 + 1.5	12:08 − 0.7
2:40 − 3.7	11:12 + 2.8	11:14 + 4.4	8:24 + 2.1	1:08 − 0.3
3:33 − 2.4	11:59 + 1.5	12:06 + 3.5	9:18 + 2.5	2:15 + 0.7
4:12 − 1.8	1:38 − 0.9	2:38 + 0.8	10:14 + 2.5	3:06 + 0.7
5:04 + 0.1	3:20 − 1.8	5:42 − 2.1	11:10 + 2.7	4:16 + 2.0
6:12 + 2.1	4:10 − 1.7	8:02 − 1.6	12:05 + 3.1	5:14 + 2.8
7:08 + 2.3	5:13 − 0.6	9:09 − 0.6	2:07 + 3.1	5:54 + 2.9
8:06 + 3.0	5:51 + 0.5	10:10 + 0.8	4:18 + 2.1	7:00 + 2.8
9:08 + 3.0	7:17 + 3.1	11:19 + 1.5	6:19 + 0.6	8:10 + 2.4
10:20 + 1.0	8:05 + 4.3	12:16 + 2.5	7:10 − 0.2	9:22 + 1.5
11:28 − 1.4	9:22 + 5.0	1:22 + 2.2	8:22 − 0.8	10:06 + 1.0
12:20 − 2.5	C= −1.32	2:08 + 1.2	9:12 − 1.2	11:12 + 0.3
2:11 − 3.6		3:23 + 0.4	10:16 − 1.0	12:22 + 0.3
4:18 − 1.2	10:12 + 4.7	4:10 + 0.8?	11:14 − 1.1	2:10 + 0.8
8:20 + 3.8	11:14 + 3.2	5:01 + 0.3	12:01 − 1.1	4:25 + 2.5
9:14 + 3.3	12:10 + 1.2	5:58 + 0.7	1:04 − 0.6	6:16 + 3.3
10:08 + 3.1	2:10 − 2.4	7:16 + 2.2	2:08 + 0.3	7:20 + 3.1
11:18 − 0.2	4:16 − 4.6	8:02 + 2.5	3:06 + 0.9	8:13 + 2.0
11:58 − 1.2	6:28 − 3.4	9:06 + 3.5	4:10 + 1.2	9:08 + 1.3
1:19 − 3.0	7:15 − 1.8	10:16 + 4.6	5:08 + 1.7	10:08 + 0.5
2:06 − 3.3	8:22 − 1.4	11:08 + 4.7	6:02 + 1.8	11:10 − 0.7
3:10 − 3.0	9:10 + 0.6	12:12 + 4.4	7:17 + 1.5	11:58 − 1.4
4:20 − 1.2	10:05 + 1.5	2:09 + 2.4	8:08 + 1.4	1:10 − 0.8
5:21 + 0.8	11:12 + 1.6	4:20 + 0.3	9:05 + 1.3	2:10 − 0.5
6:49 + 2.9	12:00 + 1.1	6:39 − 1.1	10:12 + 1.8	3:12 + 0.4
8:32 + 4.4	1:08 + 0.4	7:40 − 1.2	11:11 + 1.7	4:10 + 1.3
9:50 + 3.5	2:21 − 1.0	9:10 − 0.5	12:05 + 1.7	5:12 + 2.3
11:15 + 1.2	3:09 − 1.4	10:33 ± 0.0	2:16 + 1.9	5:59 + 2.8

TABLE III—*Continued*

P.M. October 10	P.M. October 13	A.M. October 16	P.M. October 18	P.M. October 21
6:53 + 2.9	1:18 − 2.9	6:00 − 4.1	6:51 − 2.4	2:12 − 6.7
8:10 + 2.2	2:24 − 2.9	7:13 − 2.4	8:30 − 0.9	3:20 − 6.4
9:18 + 1.4	3:27 − 1.9	8:02 − 1.4	9:52 − 0.2	4:10 − 6.3
10:14 + 0.3	4:14 − 1.0	9:06 − 0.7	11:00 − 0.7	5:04 − 6.4
11:14 − 0.8	5:11 + 0.2	10:10 − 1.0	12:00 − 1.7	6:00 − 6.0
12:34 − 1.1	5:59 + 1.3	11:06 − 1.8	2:05 − 5.3	7:00 − 5.9
1:50 − 1.1	6:52 + 2.2	12:06 − 2.5	4:06 − 7.9	8:02 − 5.8
4:11 + 0.2	8:17 + 2.5	1:14 − 4.0	6:11 − 8.0	9:26 − 5.1
6:12 + 1.7	9:16 + 1.9	2:12 − 4.3	7:16 − 7.3	10:16 − 4.7
7:12 + 2.0	10:12 + 0.7	3:12 − 4.1	8:03 − 6.2	11:10 − 4.2
8:18 + 1.3	11:10 − 1.0	4:14 − 3.6	9:09 − 5.5	12:05 − 4.2
9:08 ± 0.0	12:07 − 2.5	5:18 − 2.6	10:08 − 4.1	1:08 − 3.9
10:18 − 1.0	2:13 − 4.2	6:52 − 0.3	11:03 − 4.0	2:00 − 4.4
11:14 − 2.2	4:16 − 3.4	8:14 + 0.9	2:03 − 4.3	4:11 − 5.5
12:02 − 2.6	6:14 − 0.5	9:09 + 1.1	3:02 − 4.7	6:14 − 7.6
1:10 − 2.8	7:09 + 0.8	10:09 + 0.9	4:04 − 5.2	7:12 − 8.6
2:04 − 2.8	8:21 + 1.3	11:09 − 0.6	5:04 − 5.2	8:13 − 9.0
3:18 − 1.9	9:20 + 0.9	12:12 − 2.3	6:12 − 4.9	9:14 − 9.1
4:06 − 0.7	10:10 + 0.4	2:14 − 5.4	7:58 − 3.1	10:10 − 8.6
5:01 + 0.4	11:04 − 0.8	4:26 − 6.6	9:15 − 1.9	11:08 − 8.5
5:51 + 1.3	12:01 − 2.1	6:06 − 5.0	10:08 − 1.8	12:00 − 7.8
6:56 + 1.8	1:06 − 2.7	7:14 − 3.4	11:02 − 1.8	1:09 − 7.2
8:11 + 1.6	2:17 − 3.3	8:10 − 2.5	12:06 − 2.7	2:11 − 6.6
9:26 + 0.4	3:09 − 2.3	9:04 − 1.7	2:10 − 5.0	3:05 − 6.3
10:15 − 0.7	4:08 − 1.7	10:00 − 1.6	4:12 − 7.9	4:04 − 6.2
11:10 − 2.1	5:02 − 0.6	11:05 − 2.0	6:55 − 8.9	5:07 − 6.1
12:11 − 3.1	5:41 + 0.3	12:00 − 2.8	8:12 − 8.0	6:44 − 6.3
2:12 − 3.2	7:03 + 2.0	1:08 − 3.5	9:10 − 7.4	8:01 − 6.3
4:05 − 1.5	8:06 + 2.7	1:54 − 4.1	10:16 − 6.5	9:03 − 6.5
6:10 + 0.7	9:05 + 2.4	3:20 − 4.9	11:10 − 6.3	10:08 − 6.3
7:40 + 1.1	10:06 + 0.9	4:10 − 4.4	12:02 − 6.0	12:09 − 5.3
8:46 + 0.6	11:02 − 0.5	5:10 − 3.5	1:07 − 6.5	1:56 − 4.9
9:46 − 1.0	12:05 − 2.6	5:49 − 2.7	2:08 − 6.8	4:08 − 4.9
10:52 − 1.3	3:31 − 5.2	7:14 − 0.9	3:17 − 7.1	6:06 − 6.5
11:53 − 2.3	5:10 − 4.5	8:10 + 0.2	4:07 − 7.1	7:21 − 7.9
12:51 − 2.8	6:39 − 1.3	9:08 + 0.7	5:06 − 7.3	8:34 − 8.7
2:10 − 2.8	8:18 ± 0.0	10:23 + 0.3	5:53 − 7.0	9:26 − 9.1
2:52 − 2.3	9:11 + 0.2	11:20 − 0.6	6:58 − 6.6	10:16 − 8.8
4:01 − 1.0	10:12 − 0.2	12:20 − 2.6	8:08 − 6.1	11:09 − 8.4
5:06 + 0.2	11:05 − 0.8	2:06 − 5.3	9:16 − 4.7	11:56 − 7.8
6:21 + 1.8	12:04 − 1.8	5:00 − 7.6	10:20 − 4.6	1:07 − 7.0
8:12 + 2.0	1:08 − 2.7	5:58 − 7.2	11:16 − 4.1	2:07 − 6.2
9:22 + 0.9	2:03 − 3.3	7:06 − 6.1	12:09 − 4.3	3:26 − 5.7
10:06 − 0.2	3:15 − 3.3	8:05 − 5.0	2:13 − 5.8	4:12 − 5.3
11:17 − 2.0	4:10 − 2.5	9:08 − 3.7	4:23 − 7.8	5:08 − 5.2
12:14 − 3.4	5:08 − 1.3	10:06 − 2.9	6:28 − 9.8	5:46 − 5.1
1:58 − 4.1	5:49 − 0.5	11:10 − 2.8	7:56 −10.0	7:00 − 5.6
4:26 − 2.2	7:37 + 1.8	12:02 − 2.8	9:02 −10.1	8:00 − 6.1
6:59 + 0.9	8:48 + 2.1	1:18 − 3.4	10:12 − 9.8	9:16 − 6.7
8:14 + 1.4	10:12 + 1.2	2:15 − 4.4	C= +1.30	10:18 − 6.8
9:11 + 1.1	11:16 − 0.6	3:11 − 4.0	11:21 − 8.7	11:07 − 6.8
10:13 + 0.2	12:03 − 2.2	4:04 − 4.4	12:04 − 7.6	12:24 − 6.3
11:10 − 1.1	2:06 − 5.4	4:58 − 4.1	1:08 − 7.1	2:03 − 5.2
12:10 − 1.8	4:16 − 6.0	5:48 − 3.7		4:19 − 4.1

TABLE III—*Continued*

A.M. October 24	P.M. October 26	A.M. October 29	A.M. November 1	P.M. November 3
6:06 — 5.3	6:29 — 2.8	9:10 — 4.2	12:42 — 5.3	2:11 — 4.2
7:07 — 6.2	8:05 — 3.6	10:08 — 5.0	2:20 — 8.3	3:15 — 4.3
8:11 — 7.3	9:17 — 5.1	11:12 — 6.0	4:12 — 9.9	4:10 — 3.8
9:08 — 8.2	10:16 — 6.9	12:08 — 6.9	6:06 — 9.3	5:12 — 3.7
10:05 — 9.1	12:11 — 9.6	1:10 — 8.1	7:12 — 8.8	5:50 — 3.8
11:04 — 9.3	2:02 — 9.8	2:14 — 8.0	C = −2.64	6:52 — 3.6
11:55 — 8.6	4:10 — 7.2	3:18 — 7.5		8:16 — 2.3
1:09 — 7.9	6:00 — 4.5	4:13 — 6.2	8:08 — 7.3	9:19 — 1.7
2:10 — 6.5	7:20 — 4.2	5:08 — 4.7	9:04 — 5.6	10:20 — 0.9
3:04 — 5.6	8:16 — 4.4	5:51 — 3.5	10:15 — 5.0	11:14 — 0.7
4:08 — 4.5	9:21 — 5.4	6:58 — 1.8	11:16 — 4.6	12:10 — 0.4
5:05 — 4.1	10:15 — 6.4	8:08 — 1.2	12:02 — 4.8	2:17 — 1.5
5:56 — 3.8	11:07 — 7.6	9:24 — 1.5	1:06 — 5.0	C = −1.84
6:56 — 4.4	12:02 — 8.6	10:21 — 2.9	2:09 — 5.9	
8:12 — 5.1	1:00 — 9.0	11:16 — 5.0	3:15 — 6.1	4:16 — 2.9
9:04 — 6.0	2:16 — 8.4	12:14 — 6.9	4:16 — 6.3	6:17 — 4.6
10:10 — 6.9	3:12 — 7.1	2:15 —10.7	5:20 — 6.0	7:19 — 5.2
11:16 — 7.5	4:16 — 5.5	4:16 —10.8	5:53 — 5.3	8:18 — 5.2
12:23 — 7.2	5:14 — 3.5	6:14 — 8.2	6:54 — 4.1	9:11 — 4.9
2:06 — 6.2	5:52 — 2.6	7:14 — 7.0	8:12 — 2.4	10:13 — 4.9
4:16 — 4.2	6:49 — 2.0	9:16 — 5.4	9:14 — 1.2	11:16 — 4.1
6:16 — 3.5	8:15 — 2.0	12:09 — 7.0	10:17 — 1.0	12:04 — 4.1
7:13 — 4.4	9:09 — 3.3	1:c8 — 8.0	11:21 — 1.3	1:11 — 3.4
8:10 — 5.5	10:08 — 4.9	2:05 — 8.7	12:36 — 2.6	2:16 — 3.0
9:25 — 6.7	11:12 — 7.3	3:16 — 8.3	2:19 — 5.1	3:17 — 2.7
10:22 — 7.6	12:08 — 9.1	4:15 — 7.3	4:17 — 7.4	3:28 — 2.2
11:14 — 7.9	2:13 —10.5	5:08 — 6.2	6:14 — 8.3	4:18 — 2.6
12:01 — 7.9	4:12 — 8.3	5:56 — 4.6	8:17 — 6.1	5:07 — 2.6
1:08 — 7.2	6:49 — 4.2	6:58 — 3.3	9:19 — 5.5	5:54 — 2.3
2:10 — 6.1	7:30 — 3.8	8:13 — 1.6	10:17 — 4.8	6:50 — 1.8
3:20 — 4.5	8:18 — 3.5	9:18 — 1.6	11:10 — 4.3	8:05 — 1.7
4:19 — 3.6	9:06 — 3.6	10:18 — 2.3	12:15 — 4.2	9:14 — 1.5
5:09 — 2.7	10:06 — 4.4	11:20 — 3.7	1:18 — 4.2	10:09 — 1.1
5:53 — 2.4	11:07 — 5.4	12:33 — 6.0	2:25 — 5.0	11:10 — 0.6
7:08 — 2.7	12:02 — 7.0	2:16 — 9.4	3:15 — 4.7	12:23 — 0.3
8:02 — 3.7	1:14 — 7.6	4:16 —10.6	4:14 — 4.7	2:12 — 0.6
9:13 — 5.0	C = +0.90	6:25 — 8.9	5:18 — 4.5	4:11 — 1.7
10:17 — 6.7		7:18 — 7.9	6:24 — 3.5	6:12 — 3.4
11:12 — 7.5	3:06 — 8.8	8:27 — 6.5	8:04 — 2.4	7:12 — 3.7
12:02 — 7.9	3:48 — 7.9	9:34 — 5.8	9:16 — 1.2	8:15 — 4.1
2:19 — 7.0	4:46 — 5.7	10:17 — 5.6	10:06 — 0.7	9:16 — 4.6
4:12 — 4.5	5:20 — 4.4	11:12 — 6.0	11:09 — 0.9	10:27 — 4.4
6:14 — 3.1	5:49 — 3.2	12:04 — 6.3	12:16 — 1.4	11:08 — 4.5
7:14 — 3.6	6:54 — 2.2	1:05 — 7.0	2:17 — 3.2	12:04 — 3.6
8:16 — 4.3	8:07 — 1.7	2:29 — 7.5	4:38 — 5.6	1:12 — 2.7
9:16 — 5.9	9:06 — 2.7	3:31 — 7.2	6:24 — 6.5	2:12 — 2.4
10:15 — 7.3	10:10 — 4.2	4:20 — 7.1	8:19 — 5.9	3:10 — 1.6
11:13 — 8.7	11:19 — 6.4	5:13 — 6.0	C = −0.84	4:04 — 0.9
12:09 — 9.2	12:18 — 8.4	5:56 — 4.9		5:04 — 0.9
1:14 — 8.9	2:11 —10.5	6:52 — 3.6	9:26 — 5.7	5:52 — 1.4
2:28 — 8.1	4:08 —10.1	8:22 — 2.0	10:10 — 5.0	6:51 — 1.3
3:27 — 6.7	6:10 — 6.7	9:19 — 1.3	11:12 — 4.7	8:00 — 1.5
4:14 — 5.5	7:18 — 4.9	10:10 — 1.8	12:06 — 4.2	9:45 — 1.7
5:21 — 3.5	8:18 — 4.2	11:30 — 2.8	1:08 — 4.4	11:04 — 1.4

TABLE III—*Continued*

A.M. November 6	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
1:04 − 0.9	12:06 − 3.0	8:27 + 0.4	8:00 + 5.8	1:17 + 1.5
2:19 − 0.1	1:05 − 2.4	9:23 − 0.6	9:10 + 5.4	2:30 + 1.1
4:19 − 0.7	2:13 − 1.4	10:14 − 1.6	10:07 + 4.0	3:17 + 1.0
6:17 − 1.8	3:14 − 0.5	11:10 − 2.4	11:08 + 2.2	4:06 + 1.2
7:12 − 1.7	4:18 + 0.7	12:04 − 2.8	12:08 + 0.3	5:12 + 2.3
8:04 − 2.7	5:10 + 0.8	1:04 − 2.7	2:10 − 2.5	6:24 + 4.2
9:05 − 3.5	5:55 + 1.5	1:55 − 2.6	4:16 − 2.6	8:00 + 5.7
10:07 − 4.3	6:55 + 1.6	3:08 − 1.0	6:38 + 0.1	9:17 + 6.4
11:07 − 3.9	8:03 + 0.9	4:18 + 0.7	8:06 + 1.7	10:16 + 6.7
12:07 − 3.5	9:11 − 0.3	5:11 + 1.9	9:13 + 2.3	11:06 + 6.1
1:19 − 2.8	10:10 − 1.2	5:56 + 3.1	10:10 + 2.0	12:19 + 4.5
2:12 − 1.8	11:18 − 2.3	6:59 + 3.8	11:09 + 1.5	2:07 + 1.8
3:08 − 1.5	12:20 − 2.6	8:10 + 3.8	12:07 + 0.8	4:38 − 1.4
4:06 − 0.2	2:10 − 1.8	9:11 + 2.3	1:08 − 0.4	7:22 − 0.1
5:06 ± 0.0	4:17 − 0.1	10:12 + 0.8	2:01 − 0.4	8:15 + 0.5
5:50 − 0.2	6:18 + 1.0	11:10 − 0.7	3:09 + 0.5	9:10 + 1.5
6:48 − 0.4	7:08 + 1.0	12:32 − 2.6	4:09 + 1.3	10:12 + 2.4
7:59 − 0.9	8:15 + 0.2	2:08 − 3.4	5:06 + 2.6	11:14 + 2.8
9:08 − 0.9	9:16 − 0.6	4:10 − 2.5	5:56 + 3.5	12:10 + 2.6
10:10 − 1.8	10:16 − 1.9	6:28 + 0.8	6:50 + 4.6	1:07 + 2.5
11:08 − 1.7	11:16 − 2.4	7:24 + 1.4	8:12 + 6.1	2:10 + 1.8
12:14 − 1.4	1:13 − 2.7	8:16 + 1.3	9:12 + 5.8	3:15 + 1.7
1:11 − 0.8	2:29 − 1.5	9:18 + 0.8	10:20 + 5.1	4:03 + 1.6
2:10 − 0.3	3:27 − 0.3	10:14 + 0.1	11:14 + 3.9	5:05 + 2.3
4:18 + 0.4	4:36 + 1.3	11:18 − 1.0	12:04 + 2.3	5:52 + 2.6
6:12 − 0.3	5:25 + 1.8	12:08 − 1.4	2:11 − 1.9	7:12 + 3.9
7:12 − 0.7	6:13 + 2.1	1:08 − 1.7	4:16 − 2.4	8:08 + 4.8
8:08 − 1.1	8:25 + 1.4	2:12 − 1.7	6:08 − 0.6	
9.13 − 2.4	9:18 − 0.1	3:10 − 0.7	7:58 + 1.8	C = +2.66
10:09 − 2.5	10:18 − 1.1	4:04 + 1.1	9:06 + 2.6	9:16 + 5.7
11:05 − 3.3	11:20 − 2.6	5:05 + 2.8	10:18 + 2.5	10:09 + 6.3
12:04 − 3.0	12:20 − 3.3	6:00 + 3.7	11:08 + 2.3	11:09 + 6.4
1:07 − 2.2	2:04 − 3.2	7:05 + 4.7	12:04 + 1.7	12:12 + 5.7
2:22 − 1.3	4:08 − 0.3	8:08 + 4.9	1:12 + 1.1	2:08 + 3.4
3:12 − 0.7	6:04 + 1.1	9:17 + 3.9	2:16 + 0.6	4:12 + 0.4
4:17 + 0.3	8:20 + 1.0	10:08 + 3.0	3:16 + 0.7	6:13 − 0.2
C = −2.83	9:32 − 0.2	11:08 + 1.0	4:11 + 0.8	7:30 ± 0.0
	10:51 − 1.5	12:15 − 1.0	5:16 + 2.4	8:23 + 0.9
5:12 + 0.5	12:07 − 2.4	2:27 − 3.2	5:57 + 3.5	9:19 + 1.7
5:56 + 1.0	1:10 − 2.2	4:18 − 2.0	6:51 + 4.7	10:14 + 2.1
6:52 + 1.1	2:08 − 1.4	6:12 − 0.1	8:17 + 6.4	11:10 + 2.4
7:48 + 0.2	3:08 − 0.2	7:30 + 1.6	9:13 + 6.4	12:03 + 3.1
9:16 − 0.4	4:20 + 1.3	8:26 + 2.2	10:08 + 6.3	1:12 + 3.2
10:10 − 1.7	5:16 + 2.9	9:23 + 2.0	11:05 + 5.2	2:08 + 3.0
11:13 − 2.0	5:52 + 2.9	10:12 + 1.3	12:18 + 3.1	3:05 + 2.0?
12:13 − 2.1	6:52 + 3.3	11:06 + 0.5	2:06 − 0.1	4:04 + 2.7
2:44 − 0.9	9:01 + 1.6	12:06 ± 0.0	4:22 − 1.9	5:04 + 3.4
4:24 + 0.1	10:10 + 0.4	1:03 − 0.7	6:14 − 0.8	5:53 + 3.1
6:13 + 0.2	11:13 − 1.3	2:04 − 0.6	7:12 + 0.2	6:49 + 4.0
7:22 − 0.3	12:26 − 3.4	3:12 + 0.3	8:12 + 0.9	8:08 + 5.3
8:16 − 1.1	2:10 − 3.7	4:10 + 1.3	9:09 + 1.7	9:24 + 6.2
9:12 − 1.6	4:18 − 1.8	5:15 + 2.8	10:13 + 2.5	10:11 + 6.9
10:10 − 2.3	6:14 + 0.5	5:58 + 4.0	11:10 + 2.4	11:10 + 7.4
11:09 − 3.1	7:20 + 0.8	6:50 + 4.8	12:15 + 2.2	12:11 + 7.3

TABLE III—*Continued*

A.M. November 19	A.M. November 21	A.M. November 23	A.M. November 25	A.M. November 27
2:14 + 5.8	4:12 + 6.8	6:12 + 7.0	10:06 + 4.8	11:06 + 6.3
4:15 + 3.7	6:04 + 4.8	7:11 + 6.1	11:04 + 3.8	12:08 + 5.5
6:16 + 1.7	7:15 + 4.0	8:10 + 5.1	12:06 + 3.4	12:48 + 5.2
7:16 + 1.3	8:12 + 3.4	9:10 + 3.9	1:05 + 3.6	2:05 + 4.9
8:08 + 1.3	9:09 + 3.1	10:12 + 3.2	2:05 + 4.4	3:17 + 6.2
9:21 + 2.0	10:08 + 3.2	11:08 + 2.9	3:09 + 5.9	4:17 + 7.4
10:12 + 2.4	11:12 + 3.5	12:08 + 3.4	4:10 + 7.6	5:12 + 9.1
11:08 + 3.0	12:06 + 4.3	1:12 + 4.4	5:08 + 9.0	6:17 +10.6
12:12 + 3.7	1:09 + 5.4	2:18 + 6.0	5:55 + 9.7	7:30 +11.9
1:23 + 4.0	2:10 + 6.3	3:08 + 7.1	6:54 +10.0	8:16 +11.8
2:25 + 4.1	3:03 + 7.4	4:07 + 8.4	8:10 + 8.8	9:28 +11.0
3:12 + 4.2	4:09 + 7.8	5:03 + 8.6	9:08 + 7.7	10:18 + 9.6
4:14 + 4.1	5:14 + 7.8	6:08 + 8.7	10:05 + 6.0	11:08 + 7.9
5:13 + 4.1	5:50 + 7.2	8:02 + 6.9	11:08 + 4.0	12:09 + 5.9
5:50 + 4.0	6:53 + 6.6	9:06 + 5.1	12:08 + 2.5	2:03 + 2.7
7:06 + 4.3	8:06 + 5.6	10:09 + 3.8	2:10 + 1.1	3:52 + 2.4
8:11 + 4.4	9:16 + 5.1	1:15 + 2.8	4:05 + 2.8	5:35 + 4.1
9:19 + 5.3	10:14 + 5.0	3:07 + 4.5	5:56 + 5.7	6:37 + 5.6
10:12 + 5.7	11:14 + 5.3	5:06 + 6.5	7:18 + 6.9	8:19 + 7.4
11:05 + 6.3	12:12 + 5.6	7:11 + 6.4	8:20 + 7.1	9:06 + 7.6
12:16 + 6.8	2:34 + 6.8	8:18 + 5.6	9:18 + 6.4	10:04 + 7.6
2:09 + 5.9	4:10 + 7.3	9:18 + 4.4	10:16 + 5.7	11:06 + 7.2
4:12 + 4.5	6:10 + 6.2	10:07 + 3.6	11:09 + 4.7	12:06 + 6.2
6:07 + 2.7	7:20 + 5.1	11:14 + 3.1	12:06 + 4.1	1:07 + 5.7
7:14 + 1.9	8:12 + 4.3	12:04 + 2.9	1:02 + 3.9	2:08 + 5.2
8:08 + 1.6	9:08 + 3.5	1:10 + 3.6	2:06 + 4.7	3:16 + 5.8
9:22 + 1.8	10:14 + 3.2	2:07 + 4.8	3:10 + 6.0	4:08 + 6.6
10:18 + 2.1	11:09 + 3.3	3:19 + 6.9	4:08 + 7.4	5:05 + 7.9
11:09 + 2.9	12:02 + 3.7	4:14 + 8.3	5:06 + 9.3	5:48 + 9.0
12:09 + 3.4	1:09 + 4.9	5:09 + 9.4	6:00 +10.3	6:56 +10.8
1:05 + 4.3	2:14 + 5.9	6:00 + 9.6	6:52 +11.0	7:54 +11.8
2:04 + 4.7	3:18 + 7.4	6:54 + 9.2	8:02 +11.0	8:44 +11.9
3:07 + 5.3	4:14 + 8.0	8:12 + 8.3	9:10 +10.0	10:03 +11.2
4:05 + 5.2	5:08 + 8.4	9:10 + 6.8	10:12 + 8.1	12:00 + 7.8
5:03 + 5.3	5:52 + 8.2	10:13 + 5.1	11:18 + 5.9	3:15 + 2.6
5:56 + 4.9	6:48 + 7.5	11:05 + 3.4	12:36 + 3.4	5:16 + 3.0
6:56 + 4.8	8:02 + 6.5	12:08 + 2.2	2:08 + 1.8	7:06 + 5.3
8:04 + 4.8	9:20 + 5.1	2:12 + 2.5	4:26 + 3.1	8:21 + 6.9
9:08 + 5.2	10:06 + 4.3	4:16 + 4.7	6:04 + 5.2	9:30 + 7.8
10:14 + 5.4	11:17 + 3.7	6:10 + 6.9	7:16 + 6.7	10:48 + 7.5
11:07 + 6.0	12:18 + 4.1	7:20 + 6.9	8:21 + 7.5	12:03 + 7.0
12:12 + 6.6	2:12 + 5.6	8:24 + 6.4	9:18 + 7.4	1:22 + 6.2
2:06 + 7.2	4:12 + 7.0	9:14 + 5.6	10:04 + 7.0	2:18 + 6.0

TABLE IV 10(S.−N.+C.)

A.M. September 27	P.M. September 29	P.M. October 2	A.M. October 5	P.M. October 7
C=+0.70	9:36 + 0.8	3:59 − 3.6	9:01 − 6.8	10:01 − 8.1
8:04 + 2.9	11:01 + 1.6	5:01 − 4.6	10:02 − 7.0	11:00 − 8.4
9:00 + 3.2	11:59 + 1.9	5:59 − 5.3	**C=−2.30**	11:55 − 8.5
10:00 + 3.3	2:00 + 0.9	7:02 − 5.8		2:06 − 9.0
11:04 + 3.2	3:00 − 0.9	8:00 − 5.5	11:51 − 6.3	6:20 − 7.9
12:06 + 1.9	4:02 − 2.2	8:58 − 4.9	12:52 − 6.1	6:54 − 7.6
12:58 + 0.6	5:02 − 2.8	10:20 − 3.6	2:37 − 6.8	7:56 − 7.6
2:00 − 0.9	6:06 − 2.8	11:17 − 3.2	3:56 − 7.3	8:58 − 7.7
2:58 − 1.8	7:10 − 2.9	12:19 − 2.3	5:08 − 6.9	10:12 − 7.9
3:56 − 3.0	8:09 − 1.9	1:51 − 2.5	6:18 − 7.4	11:06 − 8.5
5:03 − 2.2	9:43 ± 0.0	3:05 − 2.8	7:55 − 8.2	12:06 − 9.2
5:58 − 0.9	10:52 + 0.4	4:04 − 3.6	9:12 − 8.0	1:00 − 9.4
6:54 − 0.1	2:08 − 0.1	6:29 − 5.6	10:18 − 8.6	1:59 − 9.3
8:02 + 0.7	3:10 − 1.9	7:49 − 6.1	11:55 − 8.7	3:01 − 9.1
9:03 + 2.0	4:05 − 3.2	8:58 − 6.2	2:12 − 8.1	3:58 − 9.1
C=+0.80	5:02 − 3.9	10:12 − 5.8	4:02 − 7.9	5:01 − 8.6
10:13 + 2.8	6:04 − 4.2	10:56 − 4.9	6:20 − 8.2	6:00 − 8.4
11:01 + 2.7	6:57 − 3.8	12:16 − 4.1	8:24 − 8.2	6:56 − 7.9
12:02 + 1.9	8:06 − 2.7	1:10 − 3.6	9:08 − 8.4	7:58 − 7.7
1:52 − 0.1	10:20 − 1.0	2:04 − 3.4	10:09 − 8.8	9:15 − 7.6
3:48 − 2.0	1:31 − 0.7	3:04 − 3.5	11:12 − 8.5	10:26 − 7.9
5:56 − 1.2	3:14 − 1.4	4:05 − 4.0	12:24 − 9.0	12:12 − 8.5
9:18 + 1.5	4:06 − 3.2	4:54 − 4.7	1:15 − 9.1	1:45 − 9.1
10:18 + 2.6	5:13 − 4.0	5:58 − 5.2	2:08 − 9.0	4:08 − 9.3
11:04 + 2.5	6:18 − 5.0	6:50 − 5.7	3:09 − 8.9	6:00 − 8.7
12:13 + 1.9	7:24 − 4.7	**C=+1.10**	4:04 − 8.5	6:58 − 7.6
1:26 + 0.7	8:25 − 3.6		**C=−1.76**	7:54 − 7.5
2:32 − 1.3	10:48 − 1.7	8:08 − 6.0		9:04 − 7.4
3:23 − 2.3	12:10 − 0.9	9:37 − 5.0	4:53 − 8.5	9:56 − 7.9
4:03 − 2.3	1:22 − 1.5	11:04 − 4.4	6:04 − 8.0	11:02 − 8.6
4:54 − 2.5	3:08 − 3.2	11:56 − 3.8	6:52 − 8.1	12:16 −10.0
6:00 − 1.6	4:00 − 3.5	2:28 − 3.9	8:14 − 7.9	12:58 −10.1
6:56 − 0.7	5:04 − 4.3	5:33 − 5.1	9:08 − 8.1	2:23 −10.4
7:54 + 0.6	6:02 − 4.5	7:52 − 5.7	10:05 − 7.9	2:57 −10.5
8:56 + 2.0	7:04 − 5.7?	8:58 − 6.0	10:58 − 8.8	4:07 −10.5
10:04 + 2.5	8:15 − 6.1?	10:01 − 6.3	11:55 − 8.9	5:05 − 9.9
11:12 + 3.4	9:08 − 3.8	11:11 − 6.7	1:56 − 8.5	6:02 − 9.2
12:04 + 2.6	**C=+1.92**	12:06 − 5.9	4:07 − 8.2	6:52 − 8.7
1:57 − 0.1	10:03 − 2.4	1:14 − 5.5	6:09 − 8.0	8:02 − 7.9
4:06 − 2.0	11:03 − 1.0	2:00 − 5.2	6:56 − 7.5	9:15 − 7.5
8:07 − 0.3	12:00 − 1.0	3:15 − 4.9	8:12 − 8.3	9:58 − 7.3
9:03 + 0.4	1:57 − 1.2	4:01 − 4.9	9:04 − 8.1	11:03 − 7.8
9:58 + 1.6	4:01 − 3.4	4:53 − 5.3	10:08 − 8.9	12:11 − 8.4
11:10 + 1.8	6:14 − 4.7	5:47 − 5.7	11:06 − 9.4	2:00 − 9.5
12:09 + 1.6	7:06 − 5.0	7:04 − 6.1	12:12 − 9.6	4:12 −10.2
1:11 + 0.1	8:12 − 5.3	7:53 − 6.1	12:56 − 9.6	6:04 − 9.2
1:56 ± 0.0	9:01 − 5.0	8:56 − 6.4	2:00 − 9.7	7:09 − 8.8
2:58 − 1.4	9:57 − 4.4	10:04 − 6.7	2:55 −10.0	8:02 − 8.2
4:05 − 2.2	11:06 − 3.7	10:56 − 6.6	4:01 − 8.5	8:58 − 8.0
5:07 − 2.8	12:10 − 2.6	12:02 − 6.1	4:56 − 8.6	10:00 − 8.0
5:52 − 2.3	1:00 − 2.4	2:00 − 5.7	5:51 − 8.0	10:59 − 8.3
7:04 − 2.5	2:12 − 2.3	4:09 − 5.6	7:07 − 7.7	12:11 − 9.3
8:19 − 0.8	3:10 − 3.2	6:28 − 6.5	7:58 − 7.5	12:58 −10.0
		7:30 − 5.9	8:56 − 7.7	1:56 −10.2

TABLE IV—*Continued*

P.M. October 10	A.M. October 13	P.M. October 15	P.M. October 18	P.M. October 21
3:02 −10.4	9:04 − 7.3	11:08 − 6.6	3:04 − 9.3	12:11 −11.6
4:03 −10.4	10:05 − 6.9	11:54 − 6.7	3:55 − 9.8	12:57 −11.1
5:02 −10.1	11:03 − 6.6	1:56 − 7.3	4:50 −10.1	2:03 −10.9
6:07 − 9.4	12:16 − 6.8	4:07 − 8.9	5:58 −10.6	3:10 −10.2
6:46 − 8.4	1:09 − 7.4	5:53 −10.1	6:42 −10.8	4:00 −10.1
8:01 − 8.0	2:16 − 8.4	7:05 − 9.5	8:19 −11.0	4:56 −10.4
9:10 − 7.1	3:04 − 9.2	7:55 − 9.2	9:42 −10.5	5:52 −10.5
10:06 − 7.1	4:06 −10.1	8:58 − 8.1	10:52 − 9.8	6:52 −10.7
11:02 − 7.7	5:02 − 9.5	10:02 − 7.1	11:52 − 9.7	7:53 −11.1
12:26 − 8.1	6:08 − 9.1	10:58 − 6.9	1:54 − 9.0	9:17 −11.6
2:00 − 8.8	6:44 − 8.9	12:12 − 6.8	3:54 − 9.9	10:06 −11.7
4:00 − 9.3	8:06 − 7.4	1:07 − 6.9	5:59 −10.1	11:01 −12.0
6:01 − 8.3	9:08 − 6.5	2:04 − 7.6	7:05 −11.4	11:54 −12.0
7:02 − 7.9	10:02 − 5.8	3:04 − 8.2	8:15 −11.8	12:58 −11.8
8:08 − 6.7	11:00 − 5.5	4:06 − 9.2	9:00 −12.3	1:50 −11.8
8:58 − 6.7	11:58 − 5.6	5:08 −10.2	9:59 −11.8	4:00 −11.7
10:09 − 6.3	2:02 − 7.6	6:38 −10.3	10:54 −10.9	6:05 −11.7
11:06 − 6.5	4:02 − 9.1	8:02 − 9.9	1:56 − 9.4	7:00 −11.8
12:12 − 7.1	6:03 − 9.2	8:56 − 9.4	2:54 − 9.4	8:04 −12.3
1:02 − 7.5	6:58 − 8.3	9:59 − 8.5	3:56 − 9.7	9:05 −12.9
1:54 − 8.0	8:13 − 7.5	10:58 − 7.7	4:56 −10.1	10:01 −13.0
3:10 − 8.8	9:12 − 7.1	12:00 − 7.6	6:22 −10.7	10:59 −13.4
4:00 − 9.1	10:02 − 6.4	2:02 − 8.4	7:50 −11.9	12:10 −13.2
4:55 − 8.8	10:56 − 6.4	4:16 −10.3	9:06 −11.8	1:00 −13.2
6:02 − 8.3	12:10 − 6.7	5:56 −11.1	9:59 −11.2	2:00 −12.7
6:49 − 7.7	12:58 − 7.2	7:08 −11.5	10:54 −10.8	2:57 −12.7
8:00 − 6.6	2:10 − 8.1	8:02 −10.9	11:58 −10.4	3:57 −12.3
9:18 − 5.7	3:00 − 9.3	8:55 −10.4	2:02 − 9.5	4:59 −12.0
10:08 − 5.5	4:00 −10.1	9:52 − 9.9	4:04 − 9.7	5:55 −11.8
11:03 − 5.4	4:53 −10.0	10:58 − 9.1	6:46 −10.9	6:54 −11.9
12:03 − 5.9	5:55 −10.0	12:09 − 8.5	8:03 −11.4	7:52 −11.9
2:00 − 7.3	6:53 − 9.6	12:58 − 8.2	9:04 −11.3	8:55 −12.2
3:55 − 8.6	7:58 − 8.9	2:03 − 8.3	10:10 −10.9	9:59 −12.6
6:00 − 8.1	8:55 − 7.7	3:07 − 9.3	11:02 −10.5	12:02 −13.3
7:28 − 6.8	9:55 − 6.8	4:02 −10.1	12:08 −10.0	1:47 −13.4
8:34 − 6.2	10:52 − 6.4	5:00 −10.8	12:54 − 9.5	4:00 −12.9
9:38 − 6.0	11:54 − 6.2	5:59 −11.4	2:00 − 9.1	5:56 −12.1
10:43 − 5.8	3:22 − 8.7	7:04 −11.4	3:10 − 9.2	7:12 −12.2
11:44 − 6.0	5:02 −10.2	8:00 −11.3	3:58 − 9.4	8:24 −12.5
12:44 − 6.6	6:31 −10.1	8:55 −10.6	4:56 − 9.7	9:11 −13.2
2:02 − 8.0	8:10 − 9.2	10:12 −10.0	6:02 −10.0	10:03 −13.4
2:46 − 8.8	9:03 − 8.6	11:07 − 8.9	6:48 −10.3	11:00 −14.1
3:54 − 9.1	10:04 − 7.9	12:11 − 8.5	7:58 −10.6	11:48 −14.2
4:58 − 8.9	10:58 − 7.6	1:54 − 8.1	9:04 −11.3	12:58 −14.1
6:14 − 8.2	12:12 − 7.4	4:50 −10.1	10:10 −11.2	1:58 −14.1
8:20 − 6.5	12:58 − 8.0	5:47 −10.7	11:05 −11.0	3:18 −12.8
9:14 − 6.2	1:54 − 8.3	6:58 −11.0	11:58 −10.9	4:02 −12.7
9:59 − 5.8	3:08 − 9.4	7:57 −11.2	2:02 −10.2	4:53 −12.2
11:10 − 5.4	4:03 −10.0	9:00 −11.1	4:09 −10.0	5:54 −11.6
12:06 − 5.7	5:02 −10.6	9:57 −10.3	6:14 −10.4	6:52 −11.4
1:51 − 7.3	5:58 −10.9	11:02 − 9.6	7:43 −11.1	7:54 −11.1
4:17 − 9.0	7:12 −10.3	12:10 − 9.1	8:52 −11.1	9:09 −11.2
6:50 − 8.4	8:36 − 8.6	1:12 − 8.6	10:01 −11.6	10:11 −11.9
8:07 − 7.6	10:02 − 7.4	2:07 − 8.8	11:06 −11.3	11:00 −12.5

TABLE IV—*Continued*

A.M. October 24	P.M. October 26	A.M. October 29	P.M. October 31	A.M. November 3
12:16 −13.2	3:17 −16.0	9:01 −17.5	5:04 −21.1	11:03 −21.7
1:55 −13.9	4:07 −16.0	10:00 −16.7	5:47 −21.5	12:14 −21.3
4:09 −13.6	5:14 −15.7	11:04 −16.3	6:44 −22.1	12:58 −21.5
5:56 −12.5	6:35 −14.7	12:18 −16.3	8:13 −21.9	2:04 −21.0
6:58 −12.0	8:16 −13.1	12:56 −17.0	9:08 −21.1	3:07 −20.6
8:03 −11.9	9:10 −12.4	C=−1.60	10:00 −20.8	4:02 −20.9
9:00 −12.4	10:09 −12.4		11:19 −19.9	5:04 −21.1
9:56 −12.5	12:04 −13.5	2:03 −17.9	12:34 −19.4	5:58 −21.5
10:54 −13.3	1:54 −15.6	3:05 −19.6	2:10 −19.2	6:44 −21.8
12:04 −14.3	4:01 −16.9	4:01 −20.4	4:02 −20.3	8:07 −22.4
12:59 −14.7	5:52 −16.3	5:00 −21.4	5:57 −21.6	9:07 −22.4
2:00 −15.0	7:12 −14.9	5:42 −21.7	7:18 −22.2	10:11 −22.4
2:56 −14.7	8:08 −14.1	6:48 −21.4	7:58 −22.3	11:06 −22.1
4:00 −14.1	9:16 −13.3	7:56 −20.9	8:54 −22.3	12:00 −22.3
4:55 −13.3	10:07 −13.1	9:10 −19.7	10:04 −21.4	2:06 −21.9
6:05 −12.6	11:00 −13.2	10:10 −18.4	11:08 −20.5	4:07 −22.0
6:48 −12.4	12:10 −13.9	11:04 −18.1	12:10 −19.8	6:06 −22.2
8:00 −11.8	12:52 −14.6	12:02 −18.2	1:02 −19.4	7:08 −22.6
8:55 −11.5	2:07 −15.8	C=+0.60	2:00 −19.5	8:11 −22.8
10:02 −11.8	3:03 −16.8		3:02 −19.6	9:02 −22.9
11:08 −12.6	4:08 −17.5	2:04 −19.6	4:04 −20.4	10:03 −23.1
12:16 −13.6	5:07 −17.3	4:08 −21.2	5:09 −21.1	11:08 −22.9
1:57 −14.7	6:01 −16.9	6:04 −22.2	6:02 −22.0	11:56 −22.9
4:04 −14.1	6:42 −16.5	7:05 −21.9	6:45 −22.5	1:05 −22.6
6:00 −13.2	8:04 −15.4	8:04 −21.1	8:00 −22.4	2:08 −22.5
7:03 −12.5	8:58 −14.3	9:26 −19.8	9:04 −22.5	3:09 −22.1
8:00 −12.2	9:56 −13.7	10:19 −18.9	10:06 −21.8	3:19 −21.9
9:17 −12.5	10:58 −13.7	11:06 −18.4	11:10 −21.2	4:08 −21.6
10:14 −13.0	11:58 −14.0	12:17 −18.3	12:25 −20.9	4:58 −21.4
11:05 −13.5	2:00 −16.6	12:56 −18.5	2:06 −20.2	6:02 −21.5
11:53 −14.4	4:02 −18.3	1:58 −19.0	4:05 −21.1	6:41 −21.7
12:59 −15.0	6:37 −17.8	3:02 −20.2	6:01 −21.8	7:57 −21.9
2:01 −15.8	7:20 −16.9	4:05 −21.5	8:04 −22.4	9:07 −22.2
3:12 −15.7	8:10 −16.2	4:59 −22.2	9:04 −22.5	10:00 −22.4
4:11 −15.1	8:59 −15.4	5:47 −22.6	10:09 −22.1	11:02 −22.5
5:00 −14.5	9:58 −14.9	6:48 −22.7	11:01 −21.6	12:14 −22.6
6:00 −13.9	10:59 −14.8	8:00 −22.0	12:08 −21.4	2:03 −22.3
7:01 −13.0	12:09 −15.0	9:08 −21.5	1:09 −20.8	4:00 −22.0
8:08 −12.0	1:05 −15.9	10:08 −20.6	2:17 −20.5	6:01 −22.0
9:06 −11.7	4:05 −20.2	11:10 −20.1	3:06 −20.8	7:02 −21.9
10:10 −11.9	4:34 −20.7	12:21 −19.7	4:06 −21.0	8:06 −22.2
11:04 −12.5	5:10 −20.2	2:08 −20.1	5:07 −21.7	9:02 −22.4
11:54 −13.2	5:40 −20.2	4:07 −21.8	6:34 −22.4	10:15 −22.5
2:06 −15.4	6:44 −19.5	6:17 −23.5	7:56 −22.9	10:59 −22.5
4:00 −15.7	7:57 −18.5	7:10 −23.3	9:08 −22.5	11:56 −22.5
6:03 −14.2	8:56 −17.4	8:20 −22.7	9:58 −22.5	1:05 −22.7
7:04 −13.4	10:00 −16.5	9:27 −21.6	11:01 −22.1	2:02 −22.4
8:26 −12.2	11:10 −15.9	10:07 −21.0	12:06 −21.9	3:00 −22.3
9:08 −12.1	12:10 −16.4	11:04 −19.9	2:08 −21.3	3:56 −22.1
10:07 −12.0	2:00 −18.3	12:12 −19.1	4:30 −21.4	4:56 −21.8
11:06 −12.7	3:56 −20.3	12:58 −19.0	6:14 −22.0	6:00 −21.6
12:01 −13.1	5:56 −21.1	2:22 −19.5	8:10 −22.7	6:43 −21.4
1:06 −14.3	7:05 −19.6	3:20 −20.2	9:18 −22.6	8:08 −21.4
2:20 −15.8	8:09 −18.7	4:11 −20.8	10:02 −22.4	9:37 −22.2

TABLE IV—*Continued*

P.M. November 5	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
10:56 −22.3	12:57 −23.1	9:15 −22.5	9:03 −26.8	2:24 −28.4
12:56 −23.0	2:04 −23.5	10:06 −22.7	10:00 −26.1	3:09 −28.9
2:10 −22.7	3:06 −23.8	11:04 −23.2	11:00 −25.6	3:58 −29.4
4:08 −22.5	4:10 −23.5	12:12 −23.5	12:00 −25.7	5:01 −29.9
6:07 −21.8	5:01 −23.2	12:56 −24.2	2:00 −27.1	6:16 −30.7
7:03 −21.8	6:02 −22.6	1:48 −25.0	4:08 −28.8	7:52 −30.9
7:54 −21.8	6:48 −22.0	3:01 −26.0	6:29 −29.1	9:05 −30.4
8:57 −21.8	7:55 −21.4	4:10 −26.6	8:00 −28.4	10:09 −29.7
9:59 −22.2	9:02 −21.2	5:02 −26.5	9:06 −27.5	10:58 −29.2
11:00 −22.6	10:03 −21.2	5:48 −26.3	10:02 −26.9	12:12 −28.6
11:56 −22.9	11:10 −21.7	6:46 −25.5	11:02 −26.6	1:59 −28.5
1:10 −23.4	12:14 −22.6	8:00 −24.6	11:59 −26.0	4:30 −29.8
2:03 −23.4	2:00 −23.9	9:02 −23.7	12:58 −26.3	7:09 −31.0
2:58 −22.8	4:04 −24.2	10:04 −22.9	1:54 −26.9	
3:58 −22.6	6:04 −23.2	11:00 −23.0	3:00 −28.2	C = +4.54
4:57 −22.0	6:58 −22.5	12:24 −23.4	4:00 −28.9	8:06 −31.2
5:58 −21.9	8:04 −21.8	1:58 −24.9	4:56 −29.3	9:04 −31.1
6:38 −21.3	9:04 −21.5	4:01 −26.4	6:04 −29.6	10:05 −30.8
7:50 −21.3	10:05 −21.6	6:20 −26.0	6:42 −29.8	11:06 −30.0
9:00 −21.3	11:25 −22.4	7:14 −25.4	8:04 −29.0	12:04 −29.4
10:02 −21.7	1:07 −23.7	8:06 −24.8	9:03 −28.2	1:00 −29.2
11:00 −22.0	2:22 −24.3	9:08 −24.1	10:12 −27.3	2:04 −28.9
12:08 −22.6	3:33 −24.5	10:06 −23.6	11:06 −26.9	3:07 −29.6
1:03 −22.9	4:28 −24.5	11:10 −23.7	11:57 −26.6	3:56 −30.0
2:03 −22.9	5:18 −24.1	12:16 −24.0	2:02 −27.5	4:57 −30.8
4:06 −22.5	6:06 −23.6	12:58 −24.6	4:02 −29.0	5:46 −31.8
6:03 −21.6	8:16 −21.8	2:03 −25.6	5:59 −30.0	7:02 −32.5
7:04 −21.5	9:11 −21.4	3:01 −26.5	7:49 −29.8	8:00 −32.6
8:00 −21.1	10:10 −21.4	3:57 −27.3	8:58 −29.0	9:08 −32.6
9:05 −21.1	11:13 −21.5	4:57 −27.5	10:10 −28.5	10:02 −32.5
10:02 −21.2	12:12 −22.2	5:52 −27.3	11:00 −27.8	11:00 −31.9
10:57 −21.4	1:56 −23.6	6:58 −26.8	11:55 −27.2	12:04 −31.3
11:57 −22.0	3:57 −23.9	7:59 −25.9	1:03 −27.4	2:00 −30.9
12:59 −22.4	5:55 −22.9	9:03 −25.2	2:08 −28.0	4:02 −31.2
2:12 −22.8	8:12 −21.2	9:59 −24.3	3:08 −28.5	6:03 −32.7
3:04 −22.5	9:24 −21.2	11:00 −24.2	4:04 −29.5	7:20 −33.0
4:08 −21.9	10:44 −21.4	12:08 −24.2	5:08 −30:0	8:14 −33.4
5:02 −21.7	12:14 −22.5	2:18 −26.3	5:49 −30.5	9:12 −33.3
6:01 −21.3	1:01 −23.0	4:09 −27.6	6:42 −30.5	10:04 −33.0
6:45 −20.8	2:00 −23.6	6:02 −27.7	8:09 −30.5	11:02 −32.6
7:42 −20.2	3:00 −24.3	7:22 −27.1	9:06 −29.9	11:56 −31.7
9:04 −20.3	4:06 −24.5	8:18 −26.3	10:01 −29.2	1:03 −31.3
10:03 −20.3	5:08 −24.1	9:16 −25.4	10:58 −28.6	2:00 −30.9
11:05 −20.7	5:56 −23.7	10:04 −24.9	12:10 −28.1	2:56 −30.8
12:04 −21.7	6:48 −22.5	11:00 −24.4	1:58 −28.3	3:55 −30.9
2:36 −23.0	8:54 −21.3	11:58 −24.6	4:11 −30.0	4:56 −31.0
4:11 −23.0	9:59 −20.9	12:55 −25.2	6:06 −30.8	5:46 −31.6
5:59 −22.0	11:03 −21.0	1:58 −26.0	7:04 −31.0	6:40 −32.0
7:09 −21.5	12:04 −21.4	3:06 −27.1	8:02 −31.0	8:02 −32.7
8:04 −21.4	2:01 −23.0	4:02 −28.0	9:02 −30.5	9:14 −33.0
9:00 −21.2	4:05 −24.3	5:07 −28.6	10:04 −29.7	10:00 −33.0
10:02 −21.4	6:03 −23.6	5:50 −28.9	11:01 −28.9	11:02 −32.9
11:00 −21.6	7:10 −22.8	6:42 −28.4	12:08 −28.3	12:02 −32.3
11:56 −22.1	8:20 −22.3	7:54 −27.7	1:10 −27.9	2:01 −31.7

TABLE IV—*Continued*

A.M. November 19	A.M. November 21	A.M. November 23	P.M. November 25	P.M. November 27
4:05 −32.0	4:03 −32.3	7:00 −30.8	12:13 −31.7	2:01 −34.4
6:06 −32.2	5:54 −31.7	8:00 −30.2	12:58 −32.7	3:09 −35.8
7:08 −33.0	7:08 −31.2	9:03 −30.5	1:58 −33.4	4:09 −36.7
8:00 −33.5	8:01 −31.6	10:02 −30.6	3:02 −34.4	5:03 −36.9
9:12 −33.6	9:00 −31.8	11:00 −31.1	4:02 −34.8	6:10 −36.7
10:02 −33.3	9:59 −32.3	12:00 −32.2	5:00 −34.6	7:22 −36.2
11:00 −33.0	11:02 −32.5	1:05 −32.6	5:48 −34.1	8:09 −35.5
12:02 −32.6	11:57 −32.8	2:12 −33.2	6:47 −33.6	9:20 −34.7
1:16 −32.5	1:00 −33.1	3:01 −33.2	8:00 −32.4	10:09 −33.8
1:52 −32.3	2:00 −32.7	4:00 −33.1	9:00 −31.6	11:00 −33.3
C = −1.25	2:56 −32.5	4:55 −32.4	9:57 −31.2	12:00 −33.3
	4:01 −32.0	6:02 −31.5	11:00 −31.3	1:54 −34.4
2:58 −32.3	4:55 −31.6	7:55 −30.2	12:00 −32.0	3:42 −36.1
4:04 −31.6	5:56 −31.6	8:59 −30.1	2:02 −34.0	5:28 −37.2
5:04 −31.2	6:46 −31.3	10:01 −30.1	3:57 −35.2	6:29 −37.1
5:42 −32.0	7:58 −31.3	1:07 −32.7	5:48 −35.2	8:11 −35.9
6:57 −32.0	9:10 −31.5	2:59 −33.3	7:09 −34.2	8:58 −35.1
8:03 −32.4	10:07 −32.3	4:58 −32.7	8:10 −33.1	9:58 −34.3
9:12 −33.3	11:06 −32.7	7:03 −31.0	9:10 −32.2	11:00 −33.7
10:04 −33.1	12:05 −33.2	8:10 −29.9	10:08 −31.7	12:10 −33.2
10:58 −33.6	2:25 −32.4	9:12 −29.7	11:03 −31.7	1:00 −33.4
12:06 −33.3	4:00 −32.5	10:00 −29.9	12:12 −32.4	2:01 −34.3
2:00 −32.6	6:00 −31.4	11:08 −30.9	12:56 −33.2	3:10 −35.5
4:03 −32.2	7:06 −30.9	11:58 −31.8	1:58 −34.2	4:00 −36.3
5:55 −32.1	8:00 −31.0	1:04 −32.9	3:02 −35.3	4:58 −37.0
7:04 −32.4	9:00 −31.3	2:00 −33.7	4:00 −36.0	5:54 −37.5
8:00 −32.6	10:07 −31.7	3:12 −34.1	4:57 −36.6	6:49 −37.4
9:16 −33.3	11:00 −32.1	4:07 −33.9	5:51 −36.4	8:00 −37.0
10:10 −33.3	11:54 −32.8	5:01 −33.5	6:44 −35.8	8:39 −36.4
11:00 −33.4	1:00 −33.4	5:55 −32.8	7:54 −34.5	10:10 −35.1
12:02 −33.6	2:04 −33.2	6:44 −32.1	9:00 −34.1	11:52 −34.1
12:57 −33.4	3:11 −33.3	8:04 −30.8	10:04 −33.0	3:07 −35.4
1:55 −32.9	4:06 −32.7	9:02 −30.5	11:08 −32.7	5:09 −36.9
3:00 −32.4	5:01 −32.1	10:05 −30.6	12:27 −33.4	6:58 −37.2
3:58 −32.0	5:48 −31.8	10:56 −30.9	1:58 −34.6	8:14 −36.5
4:56 −31.8	6:40 −31.2	12:00 −31.8	4:17 −36.6	9:22 −35.6
5:49 −31.6	7:54 −30.8	2:02 −33.6	5:57 −36.6	10:41 −34.7
6:46 −31.9	9:09 −31.0	4:08 −34.4	7:07 −35.6	11:56 −33.7
7:56 −32.0	9:58 −31.4	6:00 −32.9	8:14 −34.8	1:15 −33.8
9:00 −32.5	11:10 −32.1	7:11 −32.0	9:10 −33.7	2:10 −34.3
10:06 −33.0	12:12 −32.9	8:16 −31.1	9:58 −32.9	
10:59 −33.3	2:01 −33.3	9:06 −30.6	10:58 −32.8	
12:04 −33.3	4:01 −33.0	9:59 −30.3	12:01 −32.7	
1:57 −33.1	6:02 −31.4	10:57 −30.7	12:42 −33.2	

DIASTROPHISM AND THE FORMATIVE PROCESSES. V

THE TESTIMONY OF THE DEEP-SEA DEPOSITS

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Deposits laid down immediately after a deformation of the earth-shell adjust themselves more or less closely to the new inequalities of surface. This adjustment takes place at any level at which deposition occurs, shallow or deep. This follows from the nature of the case and needs no discussion. But in the stages that follow the deformation at some interval, when cumulative effects begin to be felt, the shaping of the deposits bears larger evidences of the agencies that work from the general environment and that shape into conformity with themselves the new configurations which the bottoms assume in the process of growth. In the preceding articles we have tried to draw out certain diastrophic significances from the nature of deposits laid down on shallow bottoms which, in the process of growth, came sufficiently near the water surface to be given shape by its agitation.

It falls to us now to inquire what diastrophic import there may be in the deposits of the deep sea on which surface agitation has slight effect and to which contributions from the bordering lands are limited. We may then turn to deposits that lie between the deep-sea deposits and the shelf-sea deposits, and that partake measurably of the qualities of both without having the distinctive characters of either.

The deep-sea deposits form a distinctive class sharply distinguished from sea-shelf deposits. They have been made so familiar by the labors of Sir Wyville Thompson, Sir John Murray, and their colleagues of the Challenger Expedition, and by the contributions of Professor Alexander Agassiz, the Prince of Monaco, and others, that we need here dwell only on those features that bear testimony to the nature, extent, and limitations of the diastrophism that has affected them.

By way of approach and qualification let it be noted that while these deposits mantle the bed of the deep sea very generally and must be presumed to have been essentially free from the agitating effects of sea waves and similar superficial agencies, the special locations in which such deposits accumulated most largely were yet somewhat influenced by even such currents as affect the abysmal waters. The larger part of the finely divided material of the abysmal deposits, whether it came from surface organisms or from dust or wash, floated long before it finally found lodgment at the bottom of the deep sea, and hence slight differences of motion determined whether given particles came to rest at a particular point or floated on to a quieter spot. The circulation of the deep sea is relatively gentle, but still there is the circulation actuated by the differences of temperature between the equatorial and polar regions, and the differences of density between the belts of heavy precipitation and the belts of active evaporation, not to speak of motion communicated by friction from the surface currents actuated by the winds, tides, and other familiar agencies. If the great sea basins have been essentially permanent throughout geologic history, a point we shall urge a little later, the long persistence of the currents of the deep circulation have made cumulative differences in the growth of the abysmal deposits, and some fraction, greater or less, of the undulations and the smoothed surfaces that characterize the ocean bottoms signify differences of deposition, even though the deposition at any one time has been small compared with the volume of sedimentation that took place in an equal time near the sea border. It is observed that on many submarine slopes and ridges no fine mud is deposited because of the strong currents that sweep the bottom clear.[1] In the upper half of the ocean depth the movement of the currents has been measured instrumentally; in the lower half, positive data are scant, but it is clear that the diversion of the great abysmal currents of water, as they encounter continental or other obstacles to their progress, is likely to give rise to concentrated or quickened currents at the critical points of arrest and deflection.

But, although such inequalities of deposition must be recog-

[1] Murray and Hjort, *The Depths of the Ocean* (1912), p. 272.

nized, they do not alter the great fact that the abysmal bottoms are mantled almost universally by a characteristic deposit, nor is there ground to suppose that these inequalities of deposition are sufficient to conceal any great deformation that has affected the abysmal bottoms since the earth came to mature form. Mountain ranges, if they once existed on the sea bottom, can scarcely have been seriously obscured by deep-sea deposits, and, if there have been protrusions from the sea bottom of a continental order, their configurations should still be visible.

Among the characteristics of the deep-sea deposits that have diagnostic value in our study are those especially which imply that given deposits must have been formed at given abysmal depths. There is need to consider the following factors:

(1) The relics of life that lived in the surface waters of the clear ocean or within photosynthetic depths or depths that have distinct relations to surface conditions, the pelagic life or plankton. Where the surface life mingled freely with terrigenous silt, as it generally did near extensive land, the silt tells the tale of its relationship. Where the surface life made deposits essentially free from admixture with terrigenous silts, open oceanic conditions are generally implied, but the deposits in themselves do not imply any special depth of sea. They do not even necessarily imply distance from land, for if the set of the ocean currents is constantly and steadily toward the land, the pure oceanic waters may effectively keep back the land silts and give origin to a pure oceanic deposit close up to land. So too, measurably, if currents of pure oceanic waters set steadily and persistently into mediterranean bodies of water, relatively pure pelagic deposits may be formed when the conditions are such that basal and marginal agitation is held in abeyance. When the land has been well base-leveled and is densely clothed with vegetation and bordered by sea-encroaching plants, the conditions are favorable for relatively pure oceanic deposits even in waters that indent or intersect the land. Some of the earlier extravagances in the interpretation of chalk deposits have found a check in considerations of this kind. The measure of shallowness of the bottom in such cases is likely to be revealed by the nature of the bottom life. Submerged platforms, however, when isolated

from all migratory connections with land-girting bottoms of like depth, may come to bear a pure pelagic deposit free from clear evidences of shallow-water bottom life and yet without necessarily implying any great depth.

(2) The relics of the life of the zone that lies below the superficial and photosynthetic zone and above the bottom. Normally the life relics of this median zone, as well as the relics from the surface zone above, fall together to the bottom and are there mingled with the relics of organisms that live at the bottom. Only a part of the mixture is diagnostic of depth, the benthos. A possible source of error of interpretation may arise in those areas in which the lower waters are constantly welling up and so displace the usual surface layer and more or less of its life. This displacement of the surface life is most likely to be effective where the temperature or the salinity of the rising waters is uncongenial to the surface life. In such areas the lower life is likely to follow the rising water to unusual heights and perhaps thus to vitiate more or less the usual bathymetric interpretations.

(3) The relics of the bottom life. In so far as this life is strictly confined to the bottom and can be proven to be limited to given depths, it constitutes a firm criterion for determining the depth at which the deposits containing it were formed. Positive proof that any particular form of life is strictly confined to given great depths is attended by inherent difficulties. In the great depths of the ocean basins there is a complication of the influences that affect living organisms, (1) pressure, (2) temperature, (3) salinity, (4) gas-content, as well as less tangible agencies, and it is improbable that the individual effects of these have as yet been wholly disentangled and the influence of pressure, as such, separately discriminated. *Pressure*, however, is the only true criterion of depth; the associated temperatures, salinities, and gas-contents are incidental; indeed just now they are probably the special results of the present polar phase of the deep-sea circulation; they are perhaps to be regarded as but a lingering feature of the recent glacial period, and as more or less inapplicable to other periods. It would probably be quite unsafe to assume similar temperatures, salinities, and gas-contents at all other times. In the period, for example, during

which life of sub-tropical aspect flourished in the surface seas of polar latitudes, it is not apparent how ice-cold waters could fill the abysmal depths in low latitudes as they do now; nor can similar salinities or gas-contents be safely assumed. The gas-content of the deep-sea waters at present seems clearly to be the result of high absorption in the cold polar regions where the absorption of oxygen is about doubled for a lowering of temperature of 30° C. and the absorption of carbon dioxide doubled for a lowering of about 20° C. I have elsewhere urged that there was a reversal of present deep-sea temperatures at the times when the remarkable stages of polar warmth prevailed, and that the reversal was the cause of such warmth.[1] If such reversal took place, it would probably modify rather radically the gas-content, as, by hypothesis, it did the salinity and temperature of the deep-sea waters, and hence, no doubt, their life. Whether this view be accepted or not, the difficulty of rationally postulating the persistence of ice-cold abysmal water in a stratum lying between the heated interior of the earth and a surface stratum sufficiently warm to sustain reef-growing corals in high latitudes is manifest. It is a much safer assumption that the temperature of the abysmal waters is variable, and has usually followed the climatic episodes that have dominated the earth's temperature in general.

It is almost certain that oceanic life is more responsive to such changes of temperature as occur in nature than to such changes of pressure as it usually encounters. Life is indeed seriously affected by changes of pressure that are so rapidly forced upon it as to prevent a distribution of the pressure increment or decrement throughout the tissues, but organisms do not often suffer such sudden changes in the course of nature. A change sufficiently slow to permit a gradual equalization of pressure seems to be tolerated by sea life with relative indifference. According to Murray and others some species of rather free-moving forms have a bathymetric range of 3,000 meters and more. Some species indeed seem to pass from one pressure to another in short periods without ill effects. The present adaptations of abysmal life may therefore be

[1] T. C. Chamberlin, "On a Possible Reversal of Deep-Sea Circulation and Its Influence on Geologic Climates," *Proceedings of the Amer. Phil. Soc.* (1906), Vol. XLV.

regarded rather as adaptations to existing temperatures, salinities, and gas-contents which happen to vary with depth, than as adaptations to pressure simply. The present distributions of abysmal deposits are therefore probably the products of a complex of variables of which temperature, salinity, and gas-content are not unlikely more potent than pressure.

Deep-sea deposition is at present singularly conditioned by the action of the sea-water. If the surface life were essentially uniform, and if some appreciable amount of life occupied all lower depths, as seems to be the case, the deposits of any period, if unmodified, should increase in thickness with increase of sea depth; but almost the reverse seems to be the real fact. This reversal is assigned to the solvent action of the sea-water. The larger portion of all the life relics assignable to the upper levels is wanting at the greatest depths. It is nearly absent over a large fraction of the abysmal area. The calcareous element is more largely removed than the silicious, but the latter seems to suffer also. This selective action gives to the residue of the extreme abysmal deposits their striking character more largely perhaps than any abundance of life relics that are known to be confined to great sea depths. This solvent action is most plausibly assignable at present to the exceptional absorption of oxygen and carbon dioxide in the polar seas whence it is carried to all the abysmal depths, giving them at once their low temperature and their high content of these active gases. The sections of Brennecke showing the distribution of oxygen in the North Atlantic between latitude 60° N. and 50° S. are very instructive in this respect.[1] The oxygen acting on organic matter gives rise to carbon dioxide and this, added to the original content, gives competency to dissolve the calcareous shells that fall from above. The loss of the silicious relics is not so well determined nor so well explained so far as it may be a fact.

In interpreting oceanic deposits of other ages than the present, the possibility, if not the probability, that different groups of organisms and different solvent results marked the various bathymetrical horizons, because the gas-contents, the salinities, and the temperatures were probably different, is not to be overlooked.

[1] Murray and Hjort, *The Depths of the Ocean* (1912), pp. 255, 256.

But these prudential considerations do not affect the general diagnostic nature of the oceanic deposits. They only bear on certain special bathymetrical inferences.

It appears from all the considerations that bear upon the case that the diagnostic character of the abysmal deposits is of a most declared and convincing type when broadly applied with due circumspection. Grounds for a critical attitude only arise in respect to ultra-inferences based on small remnants of ancient deposits in limited areas.

Now the broad facts are these: At the present time nearly two-thirds of the area of the earth's surface is covered by deep-sea deposits of recent origin. About one-half of the present surface is covered by truly abysmal deposits. What lies below these abysmal deposits, representing earlier periods, is unknown, because inaccessible. There is a strong presumption that similar deposits lie below the recent ones representing the earlier ages. This presumption rests on the more primary assumption that oceans of great volume existed all through those earlier ages and were giving rise to oceanic deposits, since the requisite forms of life and of débris are known to have then existed, and this, taken in connection with the even more significant fact that such abysmal deposits do not form appreciable members of the terranes of the continents, leaves no other presumption available. Sir John Murray says: "With some doubtful exceptions, it has been impossible to recognize in the rocks of the continents formations identical with those of the pelagic deposits."[1] And again he remarks: "It seems doubtful if the deposits of the abysmal areas have in the past taken any part in the formation of the existing continental masses."[2] With few exceptions, the marine members of the continental deposits belong to the shelf-sea series and to deposits of the foreset terrigenous type. These are facts of the first order of moment, and in them lies strong evidence of the permanence of the continents. The marine deposits of the continents are either epi-continental or terrigenous, the deposits of the ocean basins are oceanic and probably always have been as far back as the record permits us to go.

[1] Murray and Renard, *"Challenger" Report on Deep Sea Deposits* (1891), p. 189.

[2] *Op. cit.*, Introduction, p. xxix.

The exceptions, so far as there are any, probably all lie in the disrupted border tracts on the edge of the ocean basins or the borders of the continental protuberances, i.e., on the junction tracts between the great elevations and depressions.

The conclusion that continents and the ocean basins have been permanent in their essentials, thus so strongly supported by stratigraphical and paleontological evidence, is in complete harmony with the modern geodetic argument from the distribution of gravity and with the theory of isostasy, whichever of its phases be accepted. It is, at the same time, consonant with the dynamical inferences that spring from the deep differentiation of the specific gravities of the crust. It falls in with all the views drawn from other sources thus far set forth in this series of articles. Permanent ocean basins, gathering abysmal sediments ever since deep oceans began, alternating with permanent continents, always girt about and overlain by sea-shelf deposits and foreset bordering sediments, are regarded as the great fixed features of the earth's mature history.

The view that the continents and the oceanic basins have been permanent since the earth-body attained its maturity does not of course go so far as to affirm that there were no encroachments of the oceans upon the continents or of the continents upon the oceans, or that there were no transfers of bordering blocks or folds from the one to the other. In the very nature of the case, there must have been pressure contests along the borders, and the dividing lines may well have shifted more or less. Growth and creep seaward from the continents is assumed as probable, and periodic counter-thrusts landward from the ocean basins are assumed as more than probable. Advances and recessions on the border lines and oscillations up and down are thus of the nature of the case.

Though the continental segments, because of their lesser specific gravities and their convex attitudes, tended, when under lateral pressure, to upward movement, and the sub-oceanic segments, because of their higher specific gravities and their concave forms, tended, under lateral pressure, to downward movement and under-thrust, reversals of these natural movements would be probable in exceptional cases because of the complexity of the conditions; and so continental folds or blocks might well become abysmal, and

abysmal folds or blocks might well become continental occasionally, while, in still other cases, oscillations between the two extremes might arise. It does not militate, in any proper sense, against the view of permanency of the continental and abysmal segments, that there should be these diversities of local action on the hinge lines of the great segments.

Now there are not only simple hinge lines along the junctions of continental and abysmal segments but there are complex hinge areas, as for example areas in which the angles of a pair of continents and also the angles of a pair of abysmal segments approach one another, as the angles of the two Americas and of the Atlantic and Pacific basins, respectively, approach one another in the Antillean region, and as similar approaches are made elsewhere. These "four-corners" of the earth's segmentation are regions of exceptional instability and are affected by unusual seismic and volcanic activities.[1] In these complex hinge areas it is natural that there should be some exceptional behaviors of blocks and folds on the borders of the four contesting segments, or between them. More than that, these seem to be regions in which gigantic hooks, loops, and spits were built out from the continents, because they are regions in which conflicting shore drifts, as well as drifts of a deeper sort, actuated by the profounder currents of the great water bodies, prevailed. All the lands that lie between the massive portions of North America and South America, including Florida, Mexico, the Gulf of California, Central America, the Isthmus of Panama and the Antillean ridges, bear the aspect of gigantic hooks, loops, and spits formed in the progress of the ages between the massive nuclei of the two American continents. A similar aspect is borne by the hooks, loops, and spurs that connect southeast Asia with Australia. Less notable ridges and bridges of a similar kind appear in other junction areas.

Now if these are in reality constructive features of this kind, built out from the primitive continental segments upon the adjacent borders of abysmal segments, they cease to be typical features of either continental or abysmal type; they are rather conjoint products, with dynamic habits of their own, and they are to be interpreted on the basis of their own idiosyncracies.

[1] Chamberlin and Salisbury, *Geology* (1904), pp. 573–75.

These considerations give point to the following observations:

1. The cases in which true abysmal deposits, or close imitations of true abysmal deposits, now appear above the sea-level do not, when all are put together, appear to attain in area so much as one per cent of the total earth surface. So that, even if we assume that all cases plausibly interpreted as abysmal are truly so, the fraction of the crust in which a reversal of the dominant habit obtains is still so small that it cannot be regarded as other than exceptional.

2. So far as my present information goes, all the cases that call for serious consideration as real or plausible instances of the lifting of abysmal deposits above sea-level lie in the notable hinge areas where exceptional instability now prevails and apparently has prevailed far back in geologic history. By far the best of all cases of supposed oscillation between abysmal and subaërial attitudes is that offered by the "oceanic deposits" of the island of Barbados in the Windward group of the Lesser Antilles. To be associated with this in interpretation are the "oceanic deposits" of Trinidad, Jamaica, Cuba, and Haiti, all in the same hinge area between North and South America and between the Atlantic and Pacific basin segments. These additional oceanic deposits have not been as well studied as those of Barbados, but from what is known they seem to hamper rather than strengthen the interpretation that the Barbados deposits are really abysmal. But to this we will return later.

The supposed deep-sea deposits of Sicily are perhaps entitled to rank next to those of Barbados in type and importance. These, like the preceding, are associated with similar deposits adjacent to the Mediterranean on the north and on the south. These, like the collateral deposits of the Antilles, perhaps hamper rather than strengthen a strictly abysmal interpretation of the deposits. But neglecting this, the notable feature of the case is that these deposits lie in one of the most remarkably unstable regions of the globe, the hinge area between the more stable parts of Eurasia and the stable part of Africa. This hinge line has its eastward projection along the ancient Tethys Straits and thus becomes connected with the East Indian tract which also is one of notable instability. The

Nicobar Islands in this tract are isolated much as are the Windward Islands, and bear deposits interpreted as oceanic.

It appears therefore that all the more notable cases of this class are situated on hinge-line areas where notable flexures of the shell have been pronounced features, and where all movements are perhaps to be regarded as of a special order rather than as typical.

If we grant that all these are cases in which the crust has really oscillated from abysmal depths to atmospheric levels, they can scarcely be said to affect seriously the broad conclusion of permanency of the true continents and ocean basins drawn from the absence of abysmal deposits in the continental terranes, and from the probable presence of these beneath the recent accumulations on the abysmal segments.

Returning to the Barbados case, the gist of the local problem is found in (1) a lower deposit unquestionably formed in shallow water, (2) a middle "oceanic deposit," consisting of some beds resembling globigerina ooze and of others resembling radiolarian ooze and "Red Clay"—the group thought to imply a depression to 10,000 or 12,000 feet—and (3) an upper stratum of coralline rock, implying a return to shallow waters, and later (4) an elevation of 1,100 feet above the sea. The series has been made the subject of an elaborate study by A. J. Jukes-Brown and J. B. Harrison,[1] and of shorter papers by G. F. Franks and J. B. Harrison,[2] J. W. Gregory,[3] and J. W. Spencer.[4] The chemical, physical, and biological comparisons of Jukes-Brown and Harrison make distinctly plausible an abysmal descent between the formation of (1) and the formation of (3), during which the oceanic beds were laid down. The island stands by itself and was completely submerged; its uppermost parts are mantled by the oceanic deposit.

[1] A. J. Jukes-Brown and J. B. Harrison, "The Geology of the Barbados," *Quart. Jour. Geol. Soc. London*, XLVII (1891), 197–250; XLVIII (1892), 170–226.

[2] G. F. Franks and J. B. Harrison, "The Globigerina Marls and Basal Reef-Rocks of Barbados," *ibid.*, LIV (1898), 540–55.

[3] J. W. Gregory, "Contributions to the Paleontology and Physical Geology of the West Indies," *ibid.*, LI (1895), 255–310.

[4] J. W. Spencer, "On the Geological and Physical Development of Barbados with Note on Trinidad," *ibid.*, LVIII (1912), 354–67.

After moderate submersion, no land detritus would reach it, for it stood on the windward side of the Antilles and of South America, as the name of the group to which it belongs implies. The only deposits that could well accumulate, after this stage was reached, were those of the oceanic plankton or of the benthos, if it sank so deep. The life relics of a portion of the deposits supports the interpretation that the island actually sank to the benthos zone, but there is the alternative assumption that the benthos life and correlated conditions were carried up to unusual levels by upwelling currents about the island after it reached the stage of moderate submersion. The supposition of an elevated benthos zone might well seem gratuitous, or even an improbable special pleading, if there were not two considerations that seem to force on the case a choice between alternative special pleadings.

1. In the common interpretation it is assumed that a portion of the crust was depressed 10,000 feet or more to reach the horizon of the benthos and then raised again a somewhat greater amount, while the benthos horizon remained stationary. This is a special pleading where all the burden is thrown on crustal dynamics. This may well seem to the dynamic student as inherently improbable as an upwelling of abysmal waters carrying up the benthos zone does to the biological student.

2. On the island of Jamaica oceanic beds occur which likewise imply depression to at least moderate depths; but the summit heights of the island do not seem to have been submerged, and a similar negation seems to be predicable of Cuba and Haiti, though investigation in these cases is incomplete. The summits of none of these three islands seem to be mantled or ever to have been mantled by oceanic deposits as is the case with Barbados; they merely bear such deposits on their flanks. A special pleading that would carry these down to the usual level of the benthos requires a supplementary special pleading to account for the absence of oceanic deposits over the upper levels generally. Careful study of the whole problem is yet a thing of the future, but if this is a representative picture of the case, it would seem to be in the line of the least expenditure of energy and of the highest probability to avoid the extremes on both sides and to assume that an upwelling of the

deep sea-waters about the islands carried the benthol life and conditions to higher levels than they usually occupy now, while crustal oscillations of moderate range met this by adequate depression. This seems to explain at once, and without violence, the decided oceanic phenomena of Barbados and the divided oceanic and insular phenomena of Jamaica and the loftier islands.

But, however this may be, the total import of the distribution, positive and negative, of the deep-sea deposits furnishes a cogent argument against the view that any large part of the abysmal bottoms of the ocean basin has, at any time since the beginning of systematic stratigraphic history, been so elevated as to become a part of the present continents.

The argument has an indirect bearing on the reciprocal view that former continents have been submerged so deeply as to become parts of the present abysmal bottoms. The depression of any great continent to abysmal depths must necessarily have drawn into the cavity it left a great volume of the oceanic waters, and, if there was no reciprocal elevation of the ocean bottom elsewhere—and the preceding argument bears against that—there must have been a lowering of the sea-level about all the continents, with a profound effect on the shelf-sea work. Such profound effects have not been, I think, inferred from the stratigraphical or paleontological record itself. It is very doubtful if they can be successfully superimposed by special pleading. No great movement in any part of the complex oceanic basin can properly be assumed without specifically assigning its consequences in the changes of sea-level implied by it nor without supporting this by stratigraphical facts. Otherwise it is a speculation entertained in negligence of its physical consequences.

The direct adjudication of the hypothetically lost continents lies in a simple appeal to the configuration of the part of the sea bottom involved. It cannot reasonably be supposed that a continent could be submerged so as to completely obliterate its configuration. Its outlines should be still discernible and constitute its credentials. Without these it would seem hazardous to entertain the conception, even if there were not strong presumptions against it springing from other considerations.

There are well-known ridges on the bottoms of the oceans and others of minor order will not unlikely yet be disclosed. It is quite consistent with sound dynamics and a conservative attitude to suppose that these may have once been more bowed, or less bowed, than now, and that they may once have cut the sea surface and constituted linear islands, or land bridges, and have played their part in the migrations of plants and animals, just as present bridges may have been once submerged. And these conservative deformations, together with the oscillations and displacements of the segment borders, seem to be about the limit of probable interchange between the real continents and the real ocean basins. Their dominant feature was, as Dana, Wallace, and others long ago urged, permanency.

THE STRENGTH OF THE EARTH'S CRUST

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PART II. REGIONAL DISTRIBUTION OF ISOSTATIC COMPENSATION

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INTRODUCTION AND SUMMARY

The strength of the crust has been tested in the first part of this paper by those geologic changes which alter the surface of the earth, but not the density of its interior. If these changes in load initiate rather than merely coincide with vertical movements which serve to diminish the stress, they are thereby shown to be greater than the earth can permanently endure. If, on the other hand, the constructional forms persist, as in the two great deltas studied, then the movements which may exist in the crust due to those loads must be slower at least than the process of surface construction. Such loads consequently, unless counterbalanced by some factor not apparent, are within the limits of crustal strength.

But surface changes and the loads implied can be measured only in special cases. The previous attitude of the crust and the degree and direction of strain then existing in it are complicating factors which it is difficult quantitatively to evaluate. For these reasons the evidence yielded by geodetic investigation promises, in the end, more general and more accurate results.

It is an important conclusion, established by geodetic evidence, that the ocean basins are underlain by heavier matter than that beneath the continental platforms; the tendency through geologic time for the continents to rise relatively to the oceans may be correlated with this difference in density and the lightening of the land areas by the progressive erosion of the land surfaces. It is believed that the rejuvenative movements are in the direction of isostatic equilibrium. Fortunately for land-dwelling vertebrates, the crust is too weak for readjustment to be deferred until after the erosion of the lands, begun by the subaërial forces, shall have been completed by the sea.

But the power of geodetic research does not cease with the establishment of this cause of the maintenance of the differential relief between land surface and ocean floors. Beneath the surface of the continents it reveals heterogeneities of density and measures them against the more or less local relief above. To the extent to which areas of lighter or denser matter do not correspond to proportionately higher or lower relief, real strains either upward or downward are shown to exist through the crust. Over areas of plains which have not suffered much change for geologic ages, geodesy may thus reveal the existence of large crustal strain. On the contrary, in regions of mountainous relief, although the individual mountains are sustained by rigidity and bring local strains upon the supporting basement, geodetic study may show that there is close regional compensation of density balanced against relief, obliterating with depth the stress differences due to topography. These methods of research are thus capable of attacking the problem of the amount and direction of vertical strain existing in the crust under any part of the land surface and, to a lesser degree of accuracy, the crust beneath the sea. The breadth of the individual areas which depart from equilibrium in one direction may constitute also a vital part of the problem.

But although these are fields of research open to the geodesist, they are cultivated with much labor. The position of many stations on the surface of the earth must be determined by astronomic observations to within a fraction of a second of arc. Then a triangulation network, continent-wide, ties these together and shows

at each station, after allowing for the small errors of observation, what are the deflections of the vertical produced by the variations of relief and density. But this deflection for each station is the net result of all the relief from mean level and all the subsurface departures from the densities necessary to sustain that relief for distances of hundreds and, to a diminishing extent, even thousands of miles. The problem is made more soluble, however, by another and independent mode of attack. Observations on the intensity of gravity, when corrected for latitude, for elevation, for the surrounding relief and the density theoretically needed to sustain that relief, show the vertical component of those outstanding forces whose horizontal component was measured by astronomic determinations. It is seen that if the topography is known and its influence evaluated, and sufficient observations are reduced, the distribution of subcrustal densities and consequently the amount of crustal strains form soluble but complex problems.

The mathematical mode of investigation of such problems has, however, both its advantages and disadvantages. The advantages lie in giving quantitative results and in the test of the accuracy of the trial hypotheses by means of the method of least squares. A disadvantage lies in the necessity of erecting simple hypotheses in place of the complex realities of nature, in order to bring the data within the range of mathematical treatment. The precision of mathematical analysis is furthermore likely to obscure the lack of precision in the basal assumptions and through the apparent finality of its results tends to hide from sight other possibilities of the solution.

It is because of the geologic nature of the hypotheses on which the calculations concerning isostasy rest, and the geologic bearing of the results, that it is no act of presumption for the geologist to enter into this particular field of the geodesist.

The measurements of isostasy have been placed most fully on a quantitative basis by Hayford, and the science of geology is indebted to him in large measure. In the following consideration of the geodetic evidence attention will be confined almost entirely to his work, supplemented by that of Bowie. Hayford was the first to consider the influence of the topography and its compensation

to very great distances from each station, the first to make a considerable number of trial solutions upon various assumptions as to the depth of the zone of isostatic compensation, with the result that the reduction of the observations gave the dimensions of the earth with a considerably smaller probable error than any previous computations.[1]

But the conclusions in regard to the strength of the crust, drawn in the first part of this article from the study of deltas, stand in strong contrast to certain statements by Hayford and later by Hayford and Bowie. This second part must therefore outline the results reached by them and show what reconsiderations are necessary in order to bring into harmony their conclusions and the evidence derived from the previous geologic study. A preliminary review without criticism is given of their work in order to bring out their methods and results, and the geologic conclusions which they draw from those results. It is followed by a re-examination of the subject of regional versus local compensation. This is the problem of the size of the area over which, by virtue of the rigidity of the crust, irregularities of density and topography do not have individual relationships but do largely compensate each other over the region as a whole. It is a measure, therefore, of the areal limits of crustal strength. The tests employed by Hayford and Bowie are, as they note, indeterminate up to radii above 58.8 but less than 166.7 km. in length. Consequently Hayford did not change his opinion, based upon previous investigations, that regional compensation was limited to areas of less than one square degree. In

[1] The final publications have been issued by the United States Coast and Geodetic Survey and are as follows: Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States (up to 1906)," 1909; referred to in this paper as Hayford, 1906; Hayford, "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," 1910; referred to in this paper as Hayford, 1909; Hayford and Bowie, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," 1912; referred to in this paper as Hayford and Bowie, 1912; Bowie, "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (second paper), 1912; referred to in this paper as Bowie, 1912.

In addition Bowie has published in the *American Journal of Science*, "Some Relations between Gravity Anomalies and the Geologic Formations in the United States," (4) XXXIII (1912), 237–40.

The following discussion of their geodetic measurements and results will be confined to the work in these five papers.

this article, however, two other tests are applied which indicate that although in some areas compensation does not extend to 166.7 km. radius, in other areas it extends farther. It is concluded that the United States shows regional departures from isostasy over areas many times larger than Hayford thought to exist, as broad and in some regions probably somewhat broader than the areas of the Nile and Niger deltas, the breadth depending in considerable part upon the magnitude of the loads per unit of surface.[1]

GEODETIC MEASUREMENTS OF ISOSTASY BY HAYFORD AND BOWIE

Hayford's conclusions from deflections of the vertical.—The positions of many stations over the United States were determined with great accuracy by geodetic measurements from other stations, thus making a closed network. The positions were also determined by astronomic observation. The differences in latitude and longitude between the geodetic and astronomic positions give the observed deflections of the vertical due to the attraction of the surface irregularities and internal heterogeneities of the geoid. To account for these deflections the gravitative attraction upon the plumb-line at each station of all the topography from ocean bottoms to mountain tops within 4,126 km. was computed. The influence of the topography alone upon the direction of the vertical is known as the topographic deflection and averages a little over 30″. The average of the actually observed deflections are, however, but a fraction of this value. Consequently the excesses of volume represented by continents above oceans, and by plateaus on continents must be very largely balanced and neutralized by corresponding deficiencies of density in the crust beneath, which in turn explains how the larger relief is sustained. This is the theorem of isostasy. Various hypotheses in regard to the magnitude and distribution of these deficiencies in density under the continents, of excesses under the oceans, may be made, and the deflections recomputed on these successive suppositions and compared with the observed deflections.

[1] At the recent meeting of the Geological Society of America, December 30, 1913, to January 1, 1914, Professor W. H. Hobbs gave a paper on "A Criticism of the Hayfordian Conception of Isostasy Regarded from the Standpoint of Geology." The writer did not have the pleasure of hearing this paper, but it is clear that Professor Hobbs has attacked independently the same problems as here discussed.

The difference is the residual error due to the partial incorrectness of a hypothesis. The exactly correct hypothesis would reduce all residual errors to zero except for the errors of observation and computation. A hypothesis which approximates to the truth will give small residual errors. In a large mass of data the sum of the squares of the residuals as derived from different hypotheses serves as a test of the relative agreement of the hypotheses with nature, that hypothesis applying best for which the sum of the squares is a minimum. In all of the complete solutions a uniform distribution of compensation was assumed to exist from the surface to the bottom of the zone of isostatic compensation. That is, if the column under a certain portion of land was 3 per cent lighter than under a certain portion of water, then it was assumed that at any and every depth the two columns differed in density by 3 per cent. The differences abruptly terminate at the level where the two columns, the long but light land column and the short but heavy sea column, become of equal weight. At the level of this surface isostatic compensation is complete and there is hydrostatic equilibrium.

A tabulation of the probabilities of these hypotheses as applied to the whole of the United States is as follows:

TABLE III

Hypothesis	Sum of Squares of 765 Residuals
Solution B (extreme rigidity; depth of compensation infinite)	107,385
Solution E (depth of compensation 162.2 km.)	10,297
Solution H (depth of compensation 120.9 km.)	10,063
Solution G (depth of compensation 113.7 km.)	10,077
Solution A (depth of compensation zero)	18,889

The first investigation, that of 1906, favored Solution G, the final, that of 1909, as shown in this table, favored H. The most probable depth on the hypothesis of uniform compensation with depth and of equal depth of compensation for the whole United States was a little greater, being 122.2 km., 76 miles. It is seen, however, that there is but little change in the sum of the squares for a considerable range in the assumed depth. Further, Hayford states that the hypothesis of all compensation being attained in a 10-mile stratum whose bottom is at a depth of 35 miles is about as probable as the solution which he adopted.[1] Other variations in the hypothesis are also possible with about the same probable error.[2]

[1] 1906, p. 151.

[2] 1906, p. 153.

A distribution suggested by Chamberlin, of compensation greatest a little below the surface and diminishing to nothing at 178.6 miles, is also about as probable. Hayford therefore does not claim that his geodetic studies determine with precision the nature or depth of the distribution of compensation. The figure of 76 miles should therefore be used always with this reservation.

The residuals were classified into fourteen geographic groups. The most probable depths of compensation indicated for the several groups range from 66 to 305 km. According to Hayford, the evidence from these groups is, however, so weak and conflicting that he sees no indication that the depth of compensation is not constant over the whole area investigated.[1] He notes that, so far as the evidence goes, it indicates the depth of compensation to be greater in the eastern and central portions of the United States than in the western portion.[2] The subject is one which will be taken up later in the discussion of geodetic results.

In regard to the completeness of compensation, Hayford states:

> From the evidence it is safe to conclude that the isostatic compensation is so nearly complete on an average that the deflections of the vertical are thereby reduced to less than one-tenth of the mean values which they would have if no isostatic compensation existed. One may properly characterize the isostatic compensation as departing on an average less than one-tenth from completeness or perfection. The average elevation of the United States above mean sea-level being about 2,500 feet, this average departure of less than one-tenth part from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet (76 meters) thick on an average.[3]
>
> It is not intended to assert that every minute topographic feature, such, for example, as a hill covering a single square mile, is separately compensated. It is believed that the larger topographic features are compensated. It is an interesting and important problem for future study to determine the maximum size, in the horizontal sense, which a topographic feature may have and still not have beneath it an approximation to complete isostatic compensation. It is certain, from the results of this investigation, that the continent as a whole is closely compensated, and that areas as large as states are also compensated. It is the writer's belief that each area as large as one degree square is generally largely compensated. The writer predicts that future investigations will show that the maximum horizontal extent which a topographic feature may have and still escape compensation is between 1 square mile and 1 square degree. This prediction is based, in part, upon a consideration of the mechanics of the problem.[4]

[1] 1909, pp. 55–59.

[2] 1906, pp. 143, 146.

[3] 1909, p. 59.

[4] 1906, p. 169.

These conclusions imply a weakness of the crust surprising to the geologist and stand in marked contrast to those figures derived from the study of the deltas of the Nile and Niger. This subject also will be discussed later, as here it is desired to give only a summary statement of the methods and conclusions.

Hayford and Bowie on variations of gravity.—Regarding the relations of variations in gravity to isostasy, Hayford and Bowie state:

> As soon as it was evident that the proper recognition of isostasy in connection with computations of the figure and size of the earth from observed deflections of the vertical would produce a great increase in accuracy, it appeared to be very probable that a similar recognition of isostasy in connection with computations of the shape of the earth from observations of the intensity of gravity would produce a similar increase of accuracy. Logically the next step to be taken was therefore to introduce such a definite recognition of isostasy into gravity computations. Moreover, it appeared that if this step were taken it would furnish a proof of the existence of isostasy independent of the proof furnished by observed deflections of the vertical, and would therefore be of great value in supplementing the deflection investigations and in testing the conclusions drawn from them. In other words, the effects of isostasy upon the direction of gravity at various stations on the earth's surface having been studied, it then appeared to be almost equally important to investigate the effects of isostasy upon the intensity of gravity.[1]

In order to make the computations, the isostatic compensation was assumed to be complete under every topographic feature and uniformly distributed to a depth of 114 km. below sea-level, producing hydrostatic equilibrium at this depth. The mean density of 2.67 was taken as applying to the whole zone to this depth. Under land 3 km. high this gives a density of 2.60 from sea-level to a depth of 114 km.; under ocean 5 km. deep a density of 2.74 from ocean bottom to 114 km. below the bottom.[2]

The authors show that the topography and its compensation for the whole earth must be taken into consideration. On these assumptions the theoretic value of gravity was computed for every station, 124 in the final publication. This computed value is subtracted from the observed value and gives the "new-method" anomaly for each station. The results are shown in Fig. 5.

[1] Hayford and Bowie, 1912, p. 5.

[2] Hayford and Bowie, 1912, pp. 9, 10.

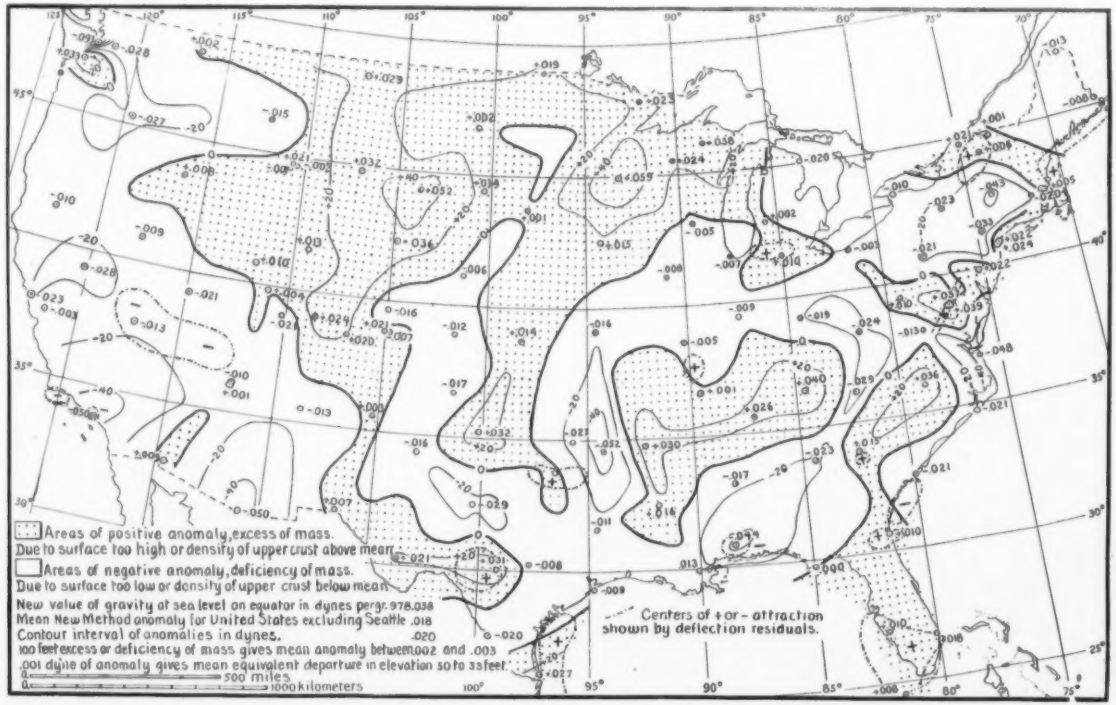
Areas of positive anomaly, excess of mass.
Due to surface too high or density of upper crust above mean.
Areas of negative anomaly, deficiency of mass.
Due to surface too low or density of upper crust below mean.
New value of gravity at sea level on equator in dynes per gr. 978.038
Mean New Method anomaly for United States excluding Seattle .018
Contour interval of anomalies in dynes. .020
100 feet excess or deficiency of mass gives mean anomaly between .002 and .003
.001 dyne of anomaly gives mean equivalent departure in elevation so to 33 feet.
500 miles
1000 kilometers
Centers of + or − attraction shown by deflection residuals.

FIG. 5.—Lines of equal anomaly for new method of reduction, after Bowie

Of the two other principal methods of gravity reduction which have been previously used, the Bouguer reduction takes no account of isostatic compensation, postulating a high rigidity of the earth's crust, and neglects all curvature of the sea-level surface. The "free-air" reduction assumes that each piece of topography is compensated for at zero depth. These two reductions correspond thus to the limiting solutions tried for deflections of the vertical. The sum of the squares of the new method anomalies, when compared respectively with the similar sums derived from the hypothesis of rigidity and the hypothesis of compensation at depth zero, shows that the assumption of isostatic compensation uniformly distributed to a depth of 114 km. gives on the average smaller anomalies; is therefore much more probable and yields a more accurate value for the intensity of gravity. The mean anomaly of all stations in the United States without regard to sign, omitting the exceptionally large anomalies of the Seattle stations, is as follows:

New method	0.018 dyne[1]
Bouguer	0.063
Free air	0.028

The value of gravity for the United States Coast and Geodetic Survey office at Washington was determined as 980.112 dynes per gram. The mean new-method anomaly is consequently about 0.00002 of the value of gravity. The probable error of observation and computation is about 0.003 dyne. The errors may, however, frequently exceed 0.004 dyne and in rare cases may be as great as 0.010 dyne.[2] The fact that these measures of gravity are the forces acting on one gram will be understood through the rest of the paper.

Of the 124 stations, 32 have anomalies between 0.020 and 0.030, 12 have anomalies between 0.030 and 0.040.[3] Still smaller numbers of stations have higher anomalies. These anomalies measure departures in the earth's crust from the conditions of isostasy which were postulated. In the interpretation of the anomalies in terms of mass it is shown that a small excess of mass immediately below

[1] Bowie, 1912, p. 12.

[2] Hayford and Bowie, 1912, p. 79; Bowie, 1912, p. 13.

[3] Bowie, 1912, p. 13.

the station or a large excess at great depth or to one side may have the same effect. Therefore it is necessary to speak of the net effective excess or deficiency of mass.[1] A table is given showing these relations, and as a mean working hypothesis it is assumed that ordinarily each 0.0030 dyne of anomaly is due to an excess or deficiency of mass equivalent to a stratum 100 ft. thick. In the final paper it is concluded:

> From the evidence given by deflections of the vertical the conclusion has been drawn that in the United States the average departure from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet thick on an average. The gravity determinations indicate this average to be 630 feet instead of 250 feet. In neither case is the average value determined or defined with a high grade of accuracy. The difference between the two determinations of the average value is therefore of little importance. The determination given by the gravity observations is probably the more reliable of the two. Each determination is significant mainly as showing that the isostatic compensation is nearly perfect.
>
> The average elevation in the United States above mean sea level is about 2,500 feet. Therefore, from gravity observations alone the compensation may be considered to be about 75 per cent complete on an average for stations in the United States.[2]

This conclusion implies a somewhat greater rigidity to the crust than that which is stated for the deflections of the vertical, but in regard to the maximum horizontal extent which a topographic feature may have and still escape compensation the authors still express the belief that the limit is between one square mile and one square degree. "It appears from the inconclusive evidence furnished by the gravity observations that the radius of this area is probably less than 18.8 kilometers."[3]

This review of the work of Hayford on deflections of the vertical, and of Hayford and Bowie on the gravity anomalies has been given in order that the methods of the work, its bearings on the strength of the crust, and the conclusions which were reached, may be perceived. It is seen that a large difference of view as to the strength of the crust exists between this interpretation from the geodetic evidence and that from the geologic. In the following pages will be

[1] Hayford and Bowie, 1912, pp. 108–12; Bowie, 1912, p. 22.

[2] Bowie, 1912, pp. 22, 23.

[3] Hayford and Bowie, 1912, p. 102.

given a discussion which it is thought brings out certain errors in the conclusions drawn from the geodetic work and thereby reconciles the two lines of evidence.

REGIONAL VERSUS LOCAL DISTRIBUTION OF COMPENSATION

Conclusions on this topic by Hayford and Bowie.—Under this heading Hayford and Bowie state:

> The question whether each topographic feature is completely compensated for by a defect or excess of mass exactly equal in amount directly under it, or whether the topographic feature is compensated for by a defect or excess of mass distributed through a more extensive portion of the earth's crust than that which lies directly beneath it, is a very important one. The theory of local compensation postulates that the defect or excess of mass under any topographic feature is uniformly distributed in a column extending from the topographic feature to a depth of 113.7 kilometers below sea level. The theory of regional compensation postulates, on the other hand, that the individual topographic features are not compensated for locally, but that compensation does exist for regions of considerable area considered as a whole.
>
> In order to have local compensation there must be a lower effective rigidity in the earth's crust than under the theory of regional compensation only. In the latter case there must be sufficient rigidity in the earth's crust to support individual features, such as Pikes Peak, for instance, but not rigidity enough to support the topography covering large areas.
>
> Certain computations have been made to ascertain which is more nearly correct, the assumption of local compensation or the assumption of regional compensation only. In making such computations it is necessary to adopt limits for the areas within which compensation is to be considered complete. A reconnoissance showed that the distant topography and compensation need not be considered, for their effect would be practically the same for both kinds of distribution. As a result of this reconnoissance it was decided to make the test for three areas, the first extending from the station to the outer limit of zone K (18.8 kilometers), the second from the station to the outer limit of zone M (58.8 kilometers), and the third, to the outer limit of zone O (166.7 kilometers).[1]
>
> The average anomaly with regard to sign by the new method with local compensation, and the average anomaly by each of the three new-method reductions with regional distribution of the compensation are respectively −0.002, −0.001, −0.001, and −0.002 dyne. The means without regard to sign for the different distributions of the compensation are respectively, 0.020, 0.019, 0.019, and 0.020 dyne. These mean anomalies give only negative evidence.[2]

[1] Hayford and Bowie, 1912, p. 98.

[2] Bowie, 1912, p. 22.

The problem may be tested in another way.

If local compensation be true, an unusually high mountain is underlain by unusually light matter and the intensity of gravity at a station on its top is less than if the mountain was supported by regional compensation and had matter of the mean regional density below it.

If the station is much below the average level of a mountainous region, local compensation implies, on the contrary, denser matter beneath and a higher value of gravity than would be given by regional compensation. These relations result in the following principle: For stations above the mean level, if local compensation be nearer the truth the hypothesis of regional compensation would tend to show its error by large negative anomalies. If regional compensation be nearer the truth, the hypothesis of local compensation would tend to show its error by giving large positive anomalies. For stations below the mean level the reverse would be true. But for any individual station other departures from the truth of that hypothesis of isostasy which gives the basis for the calculations may have greater influences and give larger anomalies than the question to be tested. Following this principle it is stated:

> There are 22 stations in the United States in mountainous regions and below the general level and the means, with regard to sign, of the anomalies by the four methods of distribution are 0.000, +0.001, +0.003, and +0.005 dyne, while the means without regard to signs are respectively 0.017, 0.017, 0.018, and 0.019 dyne. For the 18 stations in the United States in mountainous regions and above the general level the means, with regard to sign, of the anomalies by the several methods of distribution of the compensation are +0.003, +0.003, 0.000, and −0.10 dyne. The means, without regard to sign, are respectively 0.018, 0.018, 0.017, and 0.020 dyne.
>
> The mean, with regard to sign, of the anomalies for the stations at each of the two mountain groups, indicates that the theory of regional distribution of compensation to the outer limit of zone O, 166.7 kilometers is far from the truth. So far as may be judged from the other average anomalies no one method seems to have any decided advantage (see pp. 98–102 of *Special Publication No. 10*).[1]

Review and analysis of the evidence.—The present writer does not see in these computations any support for the hypothesis of local

[1] Bowie, 1912, p. 22.

compensation of the topography to between limits of one square mile and one square degree with the added suggestion of a radius less than 18.8 km., which has been advanced on other pages by the authors.[1] These figures merely show that, to the outer limit of zone M, radius 58.8 km., and probably to outer limit of zone N, radius 99 km., one method is as good as another for purposes of computation, which is not true in nature. The errors introduced by observation and computation, the errors introduced by the lack of recognition necessary in the preliminary hypothesis regarding the irregularities in the depth and distribution of compensation—these produce effects which overshadow the small systematic differences due to the hypotheses of local versus regional compensation. For the outer limit of zone O, radius of 166.7 km., a real distinction does, however, begin to appear in the data for the two groups of mountain stations. It is, however, very small and based upon a rather too limited number of stations to give quantitative reliability to the mean. Furthermore, as discussed in detail under a later heading, there is quite possibly a real difference between the limits of regional compensation and depth of compensation in the mountain regions of the West compared to other parts of the continent. Evidence drawn from the Cordillera cannot, therefore, be applied safely to the other portions of the United States.

Let the assumption be introduced that the limits of regional compensation are variable, ranging from 100 to 500 km. in radius. Such variable limits may well exist because of several factors; first, because of a real variability in the strength of the crust; second, because the greater vertical stresses could be carried only by smaller areas. In regions of mountainous relief due to folding, or of high anomalies due to great irregularities of density, the mean size of unit areas should therefore be less. On the whole the anomalies as well as the relief appear to be somewhat greater over the western United States. Third, in regions of recent block faulting or warping the stresses have presumably been lessened from what they were immediately before the movement. Such diminution of strain could take place by the breaking-up of a large unit area of crust into smaller units with differential movement among them, as

[1] Hayford and Bowie, 1912, p. 102.

well as by vertical movement of the whole area to a level best satisfying the stress. The western United States is known to be such a region, which in the late Tertiary and up to the present has been markedly affected by block faulting and differential vertical movements.

Suppose, then, that the mean radius of regional compensation in a mountainous region is 300 km. but that unit areas exist ranging in radius from 100 to 500 km. Of mountain stations located at random, a fraction of the total number would be situated within or near areas where regional compensation did not extend to 166.7 km. Let the stations be divided into one group consisting of those below the mean regional elevation and another group above the mean regional elevation. Let the anomalies be computed successively according to hypotheses of regional compensation to successive limits and the mean of the group for each limit be taken. This is the test applied by Hayford and Bowie. It has been seen that for radii of 18.8 and 58.8 km. the results are indeterminate. For a larger radius the group anomaly might be expected to show an increase as soon as the assumed radius exceeded the actual radii of a part of the areas. Consequently, if the hypothesis be true that the areas of regional compensation are variable in size, the mean anomalies of the two groups of 22 and 18 stations, found with regard to sign to be +0.005 and −0.010 respectively for radius of 166.7 km., do not show that regional compensation on the whole does not exist to those limits. It may indicate only that some areas are less than that radius. The mean radius of regional compensation may be 166.7 km. or possibly even larger. Other tests must therefore be sought which will give a more conclusive answer.

Further, it is to be noted that the mean anomalies with regard to sign for the hypothesis of regional compensation to radius of 166.7 km., although somewhat greater than for the other hypotheses, are yet of the same order of magnitude; and in all cases are but a fraction of the mean anomaly without regard to sign. Apparently, then, the assumption of regional compensation to 166.7 km. introduces a smaller error than the assumption of uniform and complete compensation with an average specific gravity of 2.67 to a constant depth of 114 km.

The test by adjacent stations at different elevations.—There is, however, another way of using the data given for stations situated well above and below the mean elevation of mountainous regions. If a pair of stations be taken close together, one far above the mean elevation, the other far below, they will presumably, because of their juxtaposition, be affected in much the same way by the errors incident to the hypothesis of uniform compensation through a depth of 114 km., with complete compensation at that depth. In order that good results may be obtained, however, the specific gravity of the local rocks should be carefully determined in order to have a correction for the mass between the stations. The parts of the anomalies due to the irregularities and incompleteness of compensation will ordinarily have the same sign and be of nearly the same value at the adjacent stations. This is indicated by the contour lines of Fig. 5, which show that in the same region the anomalies are of sufficiently regular gradation in magnitude to make the drawing of contour lines possible. The parts of the anomalies at the high and low stations due to errors in the hypothesis of local or regional compensation will, however, be of opposite sign. If, then, the algebraic difference of the anomalies for such a pair of stations be computed for successive hypotheses of broader regional compensation, the part of the anomalies due to *vertical* imperfection of the hypothesis will be largely eliminated. The algebraic difference measures the *horizontal* imperfection of the hypothesis. That hypothesis is favored whose assumed radius of regional compensation gives a minimum value to this algebraic difference. This test may be made by combining data given on p. 100, Hayford and Bowie, with p. 15, Bowie; although, because of incompleteness of the tables, this combination gives the data for only a few of the properly situated mountain stations. The best couple of stations for the application of this test consist of 42, Colorado Springs, and 43 Pikes Peak. Somewhat more distant stations—44, Denver, and 45, Gunnison—may also be added to the group. The tabulation is shown on p. 161 (Table IV).

It is seen that for three of the four Colorado stations the absolute value of the anomaly is least with regional compensation to 166.7 km. For the fourth station it remains practically constant for

all the cases. The anomalies were not computed for greater radii. The more convincing argument, however, for regional compensation to at least 166.7 km. radius in the vicinity of Pikes Peak is the fact that the *algebraic difference* of the anomalies between the top and bottom of the mountain, stations 43 and 42, is less than one-half for regional compensation to 166.7 km. radius than for the corresponding value given by the hypothesis of local compensation. The decrease in the difference is furthermore progressive with each

TABLE IV

Number and Name of Station	Elevation of Station in Meters	Distance from Mean Elevation in Meters within 100 Miles	Anomaly with Regional Compensation within Outer Limit of			
			Local Compensation. Radius 0.0 Km.	Zone K, Radius 18.8 Km.	Zone M, Radius 58.8 Km.	Zone O, Radius 166.7 Km.
Colorado						
42. Colorado Springs	1,841	−420	−0.009	−0.009	−0.010	−0.010
43. Pikes Peak	4,293	+2,035	+ .019	+ .011	+ .006	+ .002
44. Denver	1,638	−574	− .018	− .016	− .009	− .001
45. Gunnison	2,340	−380	+ .018	+ .021	+ .026	+ .016
Mean of 42, 44, and 45		−458	− .009	− .004	+ .007	+ .005
Algebraic Difference 43−42			+ .028	+ .020	+ .016	+ .012
43−(mean of 42, 44, 45)			+ .028	+ .015	− .001	− .003
Arizona						
68. Yavapai	2,179	+512	− .001	− .001	− .001	− .009
69. Grand Canyon	849	−824	− .012	− .011	− .011	− .021
Algebraic difference 68−69			+0.011	+0.010	+0.010	+0.012

assumed widening of the zone. The result of adding the more distant stations, 44 and 45, favors regional compensation more markedly but is indeterminate between M and O. It would seem, then, that the front range of the Rocky Mountains in Colorado is upheld above the surrounding plains and parks by virtue of the rigidity of the earth.

The two stations in Arizona at 68 and 69 are well situated also to test the question of local versus regional compensation, but the

difference in the anomalies in this case is so nearly constant as to give an indeterminate answer. In the absence of more detailed statements by Hayford and Bowie the reason why the anomaly at the Grand Canyon station 69 reaches a larger *negative* value for regional compensation to 166.7 km. than for more limited compensation is not evident. The usual rule is that the progressive change in the anomaly for stations below the regional level for successive assumptions of wider regional compensation is by increments with a *plus* sign. Here, on the contrary, the change in the limits from zone M to zone O involves a *minus* increment of 0.010 in the anomaly. The cause of this reversal of sign, which the writer does not understand, seems in this case to be the cause of the indeterminate result.

Another line of evidence as to the effective limits over which the rigidity of the earth may extend is derived from a study of the grouping of the deflections of the vertical shown in illustrations 2, 3, 5, 6, Hayford, 1909, and the lines of equal anomaly for the new method of reduction, illustration No. 2, Bowie, 1912, the latter giving the basis for Fig. 5 of this article.

The test by areas of grouped residuals.—Illustration No. 5, Hayford, 1909, shows the grouping of the residuals of solution H for the north and south components of the deflections. An area with a plus sign corresponds to an excess of density to the south, or deficiency to the north. An area with a minus sign corresponds to a deficiency of density to the south, or excess to the north. A north-south chain of stations is therefore best for ascertaining the limits of the areas of north-south deflection of like sign. Such a belt extends across the United States between long. 97° and 98°, showing 9 areas covering 1,620 miles. The mean intercept is therefore 180 miles. This mean intercept must be somewhat less than the mean diameter.

Illustration No. 6, Hayford, 1909, shows the grouping of the residuals of solution H for the east and west components of the deflections. An area with a plus sign corresponds to an excess of density to the east, or deficiency to the west. An area with a minus sign corresponds to a deficiency of density to the east, or excess to the west. An east-west chain of stations is therefore best

for ascertaining the limits of the areas of like sign. Such a belt extends across the United States between lat. 38° and 39°.

The following adjustments in groups seem, however, fair to make, considering the lack of exact accuracy in any one station. At Cincinnati is a station showing small residuals opposite in sign to the stations on each side. If this is overlooked, three small groups become one of average size. In central Kansas a small minus area depending on a single observation may be likewise omitted. In western Colorado several small areas depending each upon two observations had their number diminished by one. The same was done in California. This gave 14 areas extending over 2,580 miles, a mean individual intercept of 184 miles. If 16 areas be taken, a mean value is derived of 161 miles. More weight, it is thought, is to be attached to the determination of 184 miles, and this is supported by the 180 miles shown by the north-south chain of stations.

The areas of like sign are between centers of excess and defect of mass. They are not, therefore, coincident with the areas of excess and defect, but in discussing the average size of areas, the one may be used as a measure of the other.

It may be concluded, therefore, that the deflections of the vertical show areas with departures from isostatic equilibrium in one direction and these areas average about 180 miles, 290 km., in mean intercept. The mean diameters of the areas of like sign are presumably somewhat greater. This would make the mean radius of areas of regional compensation, as indicated by similarity of sign among residuals, at least 166.7 km.—the radius of the outer limit of zone O used in the discussion of the gravity anomalies.

If we turn now to the anomalies shown by the determinations of gravity, Fig. 5, adapted from Bowie, shows their segregation into areas of like sign. The mean value without regard to sign for all stations excluding Seattle is 0.018 dyne per gram. Including the two Seattle stations the mean is 0.020 dyne. Between the contours for −0.020 and +0.020 lie tracts where the anomalies are within the mean limits. The areas of exceptionally large anomalies are above those limits. It is only these which form on this illustration well-defined inclosed areas, but even these are far from

regular in outline. The areas showing positive anomalies of more than 0.020 dyne were estimated roughly to average 130 by 240 miles across, a mean diameter of 175 miles. The areas showing negative anomalies of more than 0.020 dyne were found to average roughly about 190 by 250 miles, a mean diameter of 220 miles. The long narrow connections were neglected in making this estimate. Unit areas of more than mean anomaly may therefore be taken to average about 200 miles or 320 km. in diameter. The mean radius is therefore approximately that of the outer limits of zone O, 166.7 km.

The figures, although they correspond fairly closely to those derived from the deflections of the vertical, cannot in reality be very well compared, since these are areas selected because the anomaly rises above a certain magnitude; the others represent, on the contrary, a succession of contiguous areas between centers of excess and defect in mass without reference to magnitude. Apparently some influence blurs out the limitations of areas of small gravity anomaly. This will be discussed in a later part.

Now assume for the moment that isostatic compensation is uniform to the bottom of the zone, as postulated by the hypothesis; that is, that the residuals and anomalies are due to excesses or defects of mass which are uniformly distributed. Then, over any one area of excess or deficiency of mass, the deflections around it and anomalies within it signify a departure from compensation in one direction. This is a regional departure. If the strength of the crust was so small that it was able to support notable departures from compensation over areas of only one square degree or less, then these large unit areas could not exist. A vertical warping up or down would immediately take place until the broad region as a whole lay so close to complete compensation that its surface irregularities became subdivided into subordinate positive and negative areas of the limiting size. The sum of the excesses and defects of mass would approach zero in broad areas containing many unit departures. It would seem, therefore, that the geodetic results shown in Fig. 5, instead of indicating local compensation to limits of less than one square degree, show on the contrary a ready

capacity of the crust under the United States to carry over areas of from 5 to 10 or 15 square degrees, and exceptionally over even larger areas, departures from equilibrium greater than the mean. This agrees in order of areal magnitude with the Nile and Niger deltas. However, the influence of irregularity in the distribution of compensation with depth, and the magnitude of stress per unit area remain to be investigated.

[*To be continued*]

MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

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PART II

THE FOLDING PROCESS STUDIED IN THE PROFILE—GENERAL CONSIDERATIONS

Active and passive forces involved in folding.—So soon as we take up the mechanics of rock folding, we again encounter the vital question of the location relative to the fold of active and passive forces in the process. Among the Swiss geologists it is universally held that the active force (*Schub*) which caused the folding and slicing of the Alpine highland came from the southeast and was directed toward the northwest. This view would appear to rest upon the widely accepted notion that folds which are unsymmetrical have been produced by an active force which operated from *above* and *behind* the arch with the effect of pushing over the crown so that in later stages it overhangs the base. This conception is involved in the term "overturned fold" and its many variations.[1] If we may for the moment liken a fold to an overturned free wave upon the surface of a body of water—a so-called "white cap"—the active force which is generally assumed to produce the fold has the same direction relatively as the wind. Like the wave, the fold bends over toward the lee side because, as has been believed, the active force operates above and directly upon the arch of the fold, and not upon its base (Fig. 9, *a* and *b*). The effect of this system is a couple—two parallel forces of which one is in this case a passive force of resistance, which act in opposite directions and are separated by a certain distance referred to as the arm of the couple. In

[1] See Margerie et Heim, *Les dislocations de l'écorce terrestre, essai de définition et de nomenclature*, Zürich, 1898, p. 54. Dr. E. A. Smith has, however, given the name "underthrust folds," to what he evidently regards as exceptional cases of folding ("Underthrust Folds and Faults," *Am. Jour. Sci.* (3), XLV (1893), 305–6).

all such cases there is a tendency to produce rotation, as appears from the example of the water wave. So far as the *form* of the resulting fold is concerned, the result would be similar if the active and passive forces were to be reversed; and though conscious of an appearance of presumption in again opposing his own view to such weight of authority, the writer will endeavor to show not only that the principal active force involved in the folding of the Alps must have been directed from the northwest toward the southeast,[1] but that the mechanical difficulties which have stood in the way of a more general acceptance of the views of the Swiss geologists, with this modification in large measure disappear.

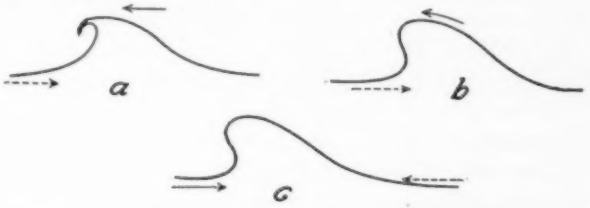


FIG. 9.—Diagrams to illustrate the active and passive forces involved in folding: *a*, position and direction of forces involved in the overturning of a free water wave; *b*, system of forces assumed by the Swiss geologists to account for the folding of the central Alps; *c*, the author's modification of this view.

It is of course to be understood that the active force tending to produce movement may not be solely from a single direction; but of the two opposed directions parallel to the chief compression, the active force as here understood is that one which represents the greater movement. If in Fig. 10 two active forces or thrusts[2] which tend to compress a given section of the earth's shell be represented in intensity by the distances *a* and *b*, the active force which becomes effective in producing unsymmetrical flexures such

[1] Willis has expressed his opposition to the conception of overturning which is apparently the standard doctrine of the day ("The Mechanics of Appalachian Structure," *13th Ann. Rept. U.S. Geol. Surv.*, 1893, Pt. II, p. 233); see also W. H. Hobbs, *Earth Features*, New York, 1912, pp. 436–38.

[2] This term is not to be confused with that generally applied to the surface of failure in folds, which latter should, we believe, be abandoned for reasons which will be given below.

as are the rule in all much compressed mountain districts is the difference between the two forces, *c*. Had the active forces *a* and *b* been just equal and the beds under compression offered uniform resistance, the folds produced should be symmetrical, and in the end have constituted a series of vertical isoclinal flexures, which are as rare in nature as they would upon this assumption be expected to be (Fig. 11).[1] The lack of a fore-and-aft symmetry in mountain arcs clearly indicates that the radially directed thrusts are not in equilibrium, but that one notably overbalances the other.

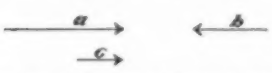


FIG. 10.—Diagram to illustrate the resultant of two parallel but opposed active forces, or that effective in producing unsymmetrical flexures.

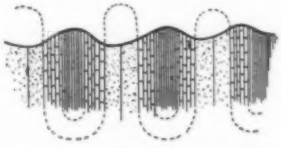


FIG. 11.—Vertical isoclinal folds

Incompetence of folding layers to transmit compressive stresses to long distances.—At the outset it is important to emphasize that the capacity of bodies to fold shows that they cannot transmit compressive stresses to long distances, due to the dissipation of energy in producing internal strains within the folding mass. With constant diminution of intensity, therefore, the active force is transmitted to certain moderate distances only from its place of application. Although perhaps self-evident, this fact has been demonstrated in experiments by Cadell, who has expressed its application to folding strata in the following sentence: "Horizontal pressure applied at one point is not propagated far forward into a mass of strata."[2] The distance to which the active force is carried

[1] This discussion obviously rests upon the assumption that the folding of any given district is due to forces from without the area itself, though independent of any special theory of planetary contraction. Any assumption which requires that the active force causing compression originate *within* the district itself requires a wholly different analysis. Thus the view of Mellard Reade, which conceives the cause of folding to be expansion by heat of areas of sediments due to depression and consequent rise (relative to the beds) of isogeotherms, would require that the active forces proceed outward toward relative rigid formations, and zones of folding should develop simultaneously on opposite margins of the more plastic interior area.

[2] Henry M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXV (1890), 356.

in sufficient intensity to produce appreciable deformation or folding may be referred to as the *reach*. In rock masses which offer a uniform resistance to folding throughout a given area, the limited reach determines that folds will begin to form upon the side which is toward the active force.[1] The very existence of an area which folds, surrounded by one which does not, implies that but for this central folding area the rock masses would be competent to transmit the tangential force without extensive deformation. The fact that folds first develop upon that side of the folding area which is toward the active force is amply demonstrated by simple experiments which were performed by Daubrée.[2] In these experiments a vertical section of the unyielding and encompassing area of the earth's shell was represented by a stiff piston-rod through which the active force was transmitted to a flexible leaden strip which therefore takes the place of the folding rock masses. When the strip of lead was made of uniform thickness, and hence of uniform strength, the folds within it formed first upon the side which was toward the piston. Only by thinning and thereby weakening the strip at the farther end could the folds be first produced at that end. The experiments of all later investigators working with materials and under conditions which must more nearly simulate those obtaining within the earth's shell have only confirmed the correctness of these simple deductions from Daubrée's experiments.

It is because of this limited reach of the deforming stress that anticlinoria which by construction imply the *simultaneous* development of similar and approximately equal anticlines throughout the length of a flatly extended arch of strata[3] are apparently unrealized in nature. Most of the supposed classical examples have been drawn from the Alps as represented upon old sections, and these may today be adequately explained upon the assumption of the development of *successive* anticlines as detailed below (p. 172).

The strength of rock formations as modified by temperature and load no doubt sets a definite limit upon the initial span of anticlines

[1] See note on Paulcke's experiments on p. 172.

[2] A. Daubrée, *Géologie expérimentale*, pp. 292–300.

[3] See, for example, Van Hise, *Principles of North American pre-Cambrian Geology*, pp. 608–9.

developed in series, and a fruitful inquiry would be to fix, by thorough examination of folded districts, the maximum span of fully disclosed, as against merely inferred, anticlinal arches.

Importance of lenses of sediments in inducing folding.—Lest too large importance be ascribed to local weakness of strata in fixing the location of initial folds, it is well to remember that folded areas do not appear to be those which are thinnest, but, on the contrary, that they are the thick lenses of sediments in which formations are present in fullest development—areas of continuous deposition in former epi-continental seas. The explanation of this fact is found in the peculiar cross-section of a lens of sediments. Obviously a perfectly straight rod of more or less rigid material whose axis is parallel to the direction of compression will transmit larger stresses than one which may be considerably thicker and stronger but is initially slightly bent from the direction of the compressive stress (Fig. 12, *a* and *b*). In the first instance (*a*), the applied force being directly opposed by the resistance, the rod tends merely to be slightly thickened, whereas in the second case (*b*), the active force is deflected parallel to the tangent to the curve, and at a rapidly accelerated rate this deflection is augmented with increasing pressure. It is thus easy to see that the cross-section of basins of deposition, being lenticular, may have been more important in favoring the location of folds than their greater thickness could have been as a hindrance. Willis, who discovered the importance in the location of folds of what he has called "initial dip," has thus stated the law of competent structure:

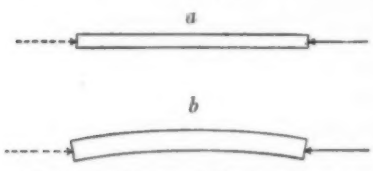


FIG. 12.—Diagram to illustrate the relative tendency to fold, or buckle, of: *a*, a straight rod; and *b*, a thicker but slightly curving rod.

> The transmission of pressure through a folding, stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the

friction on bedding planes, the viscosity of the strata, and any opposing force, as that of the load; the latter becomes active when it can cause some part of the resisting mass to move. . . . .

In strata under load an anticline arises along a line of initial dip, when a thrust, sufficiently powerful to raise the load, is transmitted by a competent stratum. The resulting anticline supports the load as an arch, and being adequate to that duty it may be called a competent structure. From the conditions of the case it follows that none other than a competent structure can develop by bending. If the thrust be not powerful enough to raise the load there will be no uplift. . . . .[1]

What has been brought out above concerning the direction of the active force would indicate that, coming as it does from the ocean basins, the thrust, instead of being influenced by initial dip at the shoreward end of a section of epicontinental deposits (which should develop there an initial syncline), is received at the off-shore end of the section and should be first diverted upward by the steeper beds upon the continental slope and so yield an initial anticline. This is, moreover, more in harmony with the results of experiment.

It seems proper to speak of the competence of an arch or anticline as its capacity in any stage of formation to lift load resting upon it.[2]

In order to simulate rock folding under as nearly as possible natural conditions, Willis in his experiments made use of layers which were of nearly uniform thickness and strength throughout and which, though sufficiently rigid to be deformed by failure under ordinary testing conditions, became potentially plastic under the load of shot which was applied in the experiments. In confirmation of the results at which one arrives from a purely theoretical treatment of the subject, it is important to note that in all Willis's experiments except when special conditions were introduced, anticlines developed on the side of the mass toward the active force

[1] *The Mechanics of Appalachian Structure*, pp. 246, 250.

[2] It is little likely that, barring exceptional cases of small anticlines, a competent stratum can lift the entire load from beds beneath, as seems to have been implied by Willis. We should in that case approach to surface conditions within a well-cemented masonry arch in which the accelerated rate of increase of weight of arch relative to its strength sets such a low limit upon the span as to be prohibitive.

or thrust, and that in successive stages of its evolution the anticline became increasingly unsymmetrical with the axial plane dipping away from the active force and finally was underthrust in the same sense. In recent experiments by Paulcke[1] which were carried out with the idea of simulating Alpine tectonics, *but with the presupposition that there had been overthrusting from behind the anticlines*, the arches were in normal cases generally either bent over toward the active (moving) force, or else a stiff plate (*Druckplatte*) was introduced and prevented their natural manner of deformation.

From the nature of rock materials we conceive that folds develop within a zone probably some miles below the earth's surface, since we believe that at such depths only can the rocks become sufficiently plastic under their load. Nearer the surface rock materials, which are normally highly elastic, must be deformed by failure or fracture, and over a rising anticline must be adjusted in block sections whose movements become manifest at the surface in earth shocks or quakes (note conditions in Bonin arc, p. 79).

A consequence of the studies by Adams, which have for the first time revealed the enormous hydrostatic compressive strengths of rocks, is certain to be a modified conception of the zone of flow (better, zone of folding) within the earth's surface shell. To assume that more than eleven miles of sediments have been eroded from those folded beds which outcrop at the earth's surface must make the hardiest theorist pause and consider whether the closing of pores necessary to permit of folding may not be due to an excess of tangential compressive force over that of the radially directed load—or, in other words, that hydrostatic conditions of compression were seldom realized in the folding of those strata, at least, which we find exposed at the earth's surface.

THE FOLDING PROCESS STUDIED IN THE PROFILE—ANTICLINE EVOLUTION

Successive sectional curves of a growing anticline.—Since, when the anticline begins to rise, the radial component of the compressive stress has the least value, and the tangential component the

[1] W. Paulcke, "Das Experiment in der Geologie," *Festschrift z. Feier des Geburtstags Seine Kön. Hoheit*, etc., herausg. v. d. Tech. Hochschule, Karlsruhe, 1912, pp. 108, figs. 44 and pls. 29. Note the *Druckplatte* in the apparatus which is figured in Pl. 8.

greatest, the span of the arch must at that time be a maximum.[1] The point from which the arch springs upon the side away from the active force thus becomes established as an abutment, so to speak, and the length of the arch is maintained constant up to a limiting stage to be presently discussed. The general shapes of simple anticlines of increasing asymmetry are well known upon the basis of experience, and the attempt has here been made to represent successive stages arbitrarily spaced in the process of anticline evolution. Six of these belong in the class denominated unsymmetrical, whereas the remaining three are "overturned" (Fig. 13). Throughout, the assumptions have been made: first, that failure of the arch does not take place; and, second, that its length remains constant—a condition which would often be realized in nature for the first six cases, but could hardly persist long after underturning had set in.

Professor Theodore R. Running of the University of Michigan, an expert in the mathematical study of curves, has at the writer's request subjected this series of curves to examination. He has found that to a close approximation the first seven of the series, the only ones which were tested, alike possess an axial line[2] which bisects all horizontal chords, and that the seven may be fitted to the comparatively simple general equation

$$y = y^{\circ}\left(\frac{a^2 - x^2}{a^2}\right)^m$$

in which the oblique co-ordinate axes are the base line and the bisecting axial line, in which y° is the length of this axial line from base to crown, and in which a is one-half the base.

Competence of a relatively strong member in an anticline to lift the load from inferior strata.—For the purposes of this discussion, the load which rests upon an anticline in competent strata may be

[1] Cf. Willis, *op. cit.*, pp. 251–52.

[2] Trace of the axial plane of the anticline. That this axial plane bisects horizontal chords of the anticline in all stages has been often noted by the writer in studying the folded schists of the Berkshire Hills of New England and elsewhere; but this character had not consciously been made a basis of measurement in drawing the curves of Fig. 13, which were made to accord with the *shapes* of anticline sections repeatedly observed in the field.

regarded as uniformly distributed throughout a horizontal plane; since, as already stated, anticline formation is believed to occur at such depths that the altitude of the arch is small by comparison. The discussion of the competence of an anticline differs from that of an arch of masonry, for the reason that the latter receives no external support in a vertical direction except at the abutments. An anticline is, upon the other hand, in part supported by the resistance to compression of the weaker formations which are arched beneath it. It may never alone support the entire load which rests upon it; but since it is stronger than immediately inferior beds, it tends always to lift from them some portion of the load. This portion varies at different parts of the arch, and for any point is roughly proportional to the cosine of the angle which the tangent at that point makes with the vertical (Fig. 14). By a summation of these values for

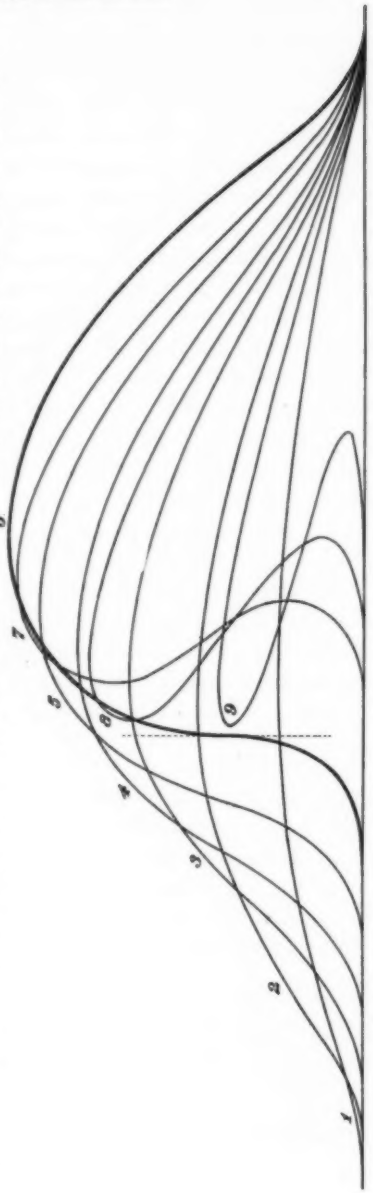


FIG. 13.—Series of successive stages of an anticline developed in a competent member within a folding series. The active force is at the left.

the entire arch a figure is obtained represented by the area *AGOHB*, which for convenience we may refer to as the "cosine area." To this there is probably to be added for the crown region particularly some part of the tangent-normal component of the load which is spent in internal strain within the arch; but since any extensive settling of the crown would bear upon the subjacent formation and transmit this burden to them, the additional amount from this source is probably so small as to be negligible in our discussion. For the different stages which we have selected in the evolution of an anticline, these cosine areas may be derived by graphical methods, and through dividing each by the total load, the percentage which is lifted by the competent member may in each case be roughly estimated.

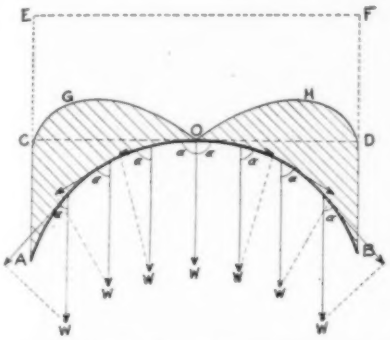


FIG. 14.—Diagram to show the proportion of total load which is lifted from underlying formations by an anticline here assumed for convenience to be the arc of a circle. *AOB*, anticline; *CDEF*, area proportional to the entire load; *AGOHB*, cosine area proportional to the load lifted from interior formation beneath the arch.

Relative competence of a member in successive stages of anticline evolution.—The cosine areas for each of the successive stages of a developing anticline which are represented in our series afford the figures of the following table:

TABLE I

Stage	Ratio of Rise to Span	Competence Figures	Percentage of the Load Lifted	Relative Volume of Anticline
1	0.073	12.6	12.6	8.6
2	.152	25.6	26.9	15.0
3	.223	34.5	37.8	19.0
4	.301	37.2	43.5	21.8
5	.361	37.8	47.9	22.8
6	.441	36.5	51.9	24.5
7	.578	29.6	50.9	18.5
8	.471	22.4	37.2	11.8
9	0.274	3.6	7.9	5.2

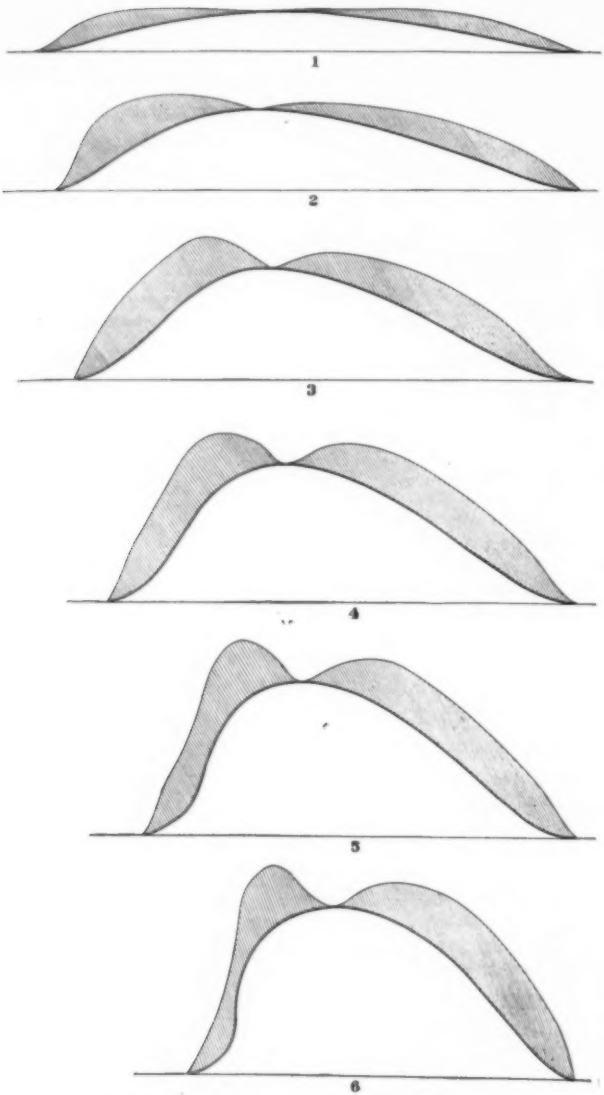


FIG. 15.—Cosine areas of the arbitrary stages 1 to 6 of a growing anticline

The drawings upon which these figures are based have been reproduced on a much reduced scale in Figs. 15 and 16. From examination of them it is learned that an anticline within a com-

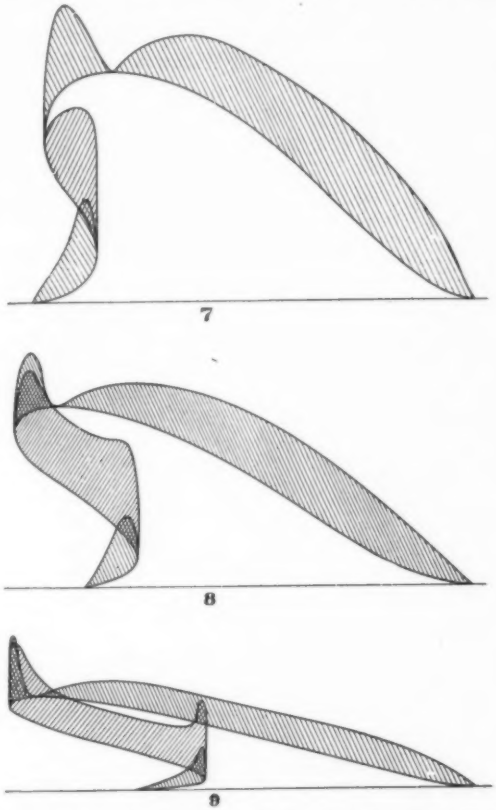


FIG. 16.—Cosine areas of the underturned stages 7 to 9 of a growing anticline (assuming, however, that the length of the arch is not increased).

petent stratum is able in its early stages, when the ratio of rise to span is relatively small, to lift but a small proportion of its load from the underlying formation; but that this competency increases beyond the arbitrary stage 1, in which the ratio of rise to span

is about $\frac{1}{10}$. Although the actual load lifted increases but little after this ratio has reached $\frac{1}{4}$, the percentage which is lifted of the total load upon the arch continues to increase up to stage 6, where underturning begins and from which point the competence falls off at a rapid rate. These deductions are graphically reproduced in Fig. 17, where the abscissae are the ratios of rise to span, and the ordinates have a different significance for each curve. The upper curve gives the percentage of total load which is lifted from inferior

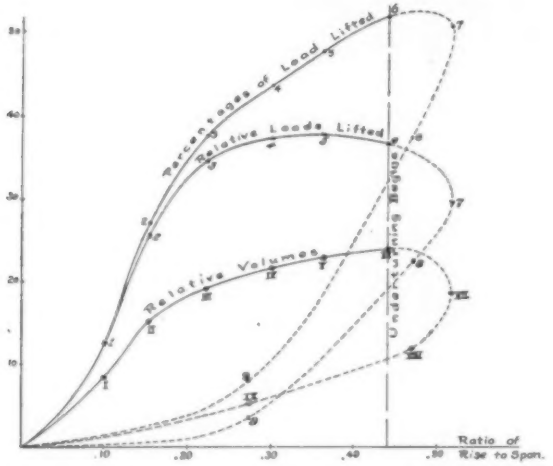


FIG. 17.—The curves of relative competency and of relative volume of an anticline in different stages up to the stage of underturning; and (in dotted lines) the purely hypothetical competence and volume on the assumption that the length of the arch is not increased after extended underturning without failure.

beds within the arch; the middle curve gives in arbitrary units the relative loads which are lifted; while the lowest curve gives in arbitrary units (not those of the middle curve) the relative volumes inclosed by the anticline.

Initiation of new anticlines in series.—The stage marked 6 in our series is where underturning begins, for the steeper limb includes a point at which the tangent to the curve is vertical. The active compressive force, which up to this stage has been deflected upward

and hence devoted to lifting the load, can no longer be thus turned out of its original course and is therefore more or less completely transmitted through the anticline to the still unfolded section of the stratum beyond (Fig. 18). At this point, therefore, the anticline has the effect of temporarily at least stiffening the stratum locally and so extending the reach of the deforming stress. Since, however, some energy is lost in the continued deformation of the original anticline, the new reach beyond the farther base will generally be less than that when the first anticline began to rise. A second arch thus tends to form behind the first, but one of somewhat smaller dimensions. This second anticline having in its turn risen to the stage of underturning, conditions for the development of a third enter; and the process may go on until continued diminution of the reach due to imperfect stiffness of the anticline series brings the process to an end.

FIG. 18.—Diagram to illustrate the initiation of new anticlines in series.

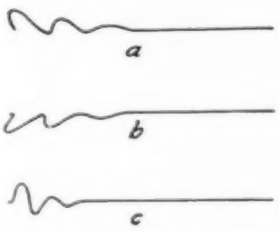


FIG. 19.—Correct (*a*) and two incorrect (*b* and *c*) representations of anticlinoria.

Successive anticlines thus developed in series are characteristic of Willis's experiments so often cited, and may be represented schematically by *a* in Fig. 19, where anticlines and synclines alike are developed *above* the original position of the stratum. Thus it is seen that though *series of arcs* develop in order from the central area of the series outward, the *series of anticlines* within each arc develop in the reverse order, or from without inward toward the central area.

Conditions of formation of plunging crowns and recumbent folds.—The peculiar curves of unsymmetrical anticlines show clearly that the horizontal external forces which produce them are so resolved as to produce rotation, and in such a sense that the base of the arch is pushed backward under the crown. This is equivalent to saying

that after the anticline has begun to rise, a couple arm separates the two opposing forces and that the point of application of the active force of compression is below that of the passive force of resistance. So soon, however, as underturning has set in, a new couple enters which involves not the compressive forces in generally horizontal positions, but the vertical external forces; namely, the load and the passive resistance of the mass to depression (Fig. 20). Within the underturned portion of the anticline this passive force

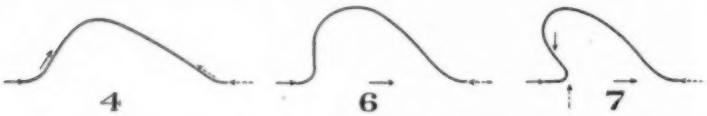


FIG. 20.—Diagrams to show the new couple which enters with the underturning of anticlines.

may be concentrated near the base of the under limb, while the load upon the underturned section of the arch is centered in front, so that the action of the couple tends to rotate the crown of the arch, not forward as before, but downward. Such sinking of the crown is resisted by any support of the superior strata which have been underfolded beneath the crown. If these are of sufficiently strong material, the crown is not bent; but in the event of their being weak, the crown is sunk as in Fig. 21. Such "plunging crowns" (*tête plongeante*, *sinkende Gewölbe*) are the normal feature in the northern zone of the Alps, where the weak Flysch (Eocene) overlies the competent Helvetian limestones.[1]

FIG. 21.—Plunging or sinking crown of an underturned anticline due to weak strata above the competent member.

Whether the crown be sunk or not, as the anticline becomes increasingly underturned, it is forced down as a whole by the action of this couple and so becomes a "recumbent fold" (Fig. 13, stage 9).

[1] For another excellent example of a plunging anticline crown see E. B. Bailey and M. Macgregor, "The Glen Orchy Anticline," *Quar. Jour. Geol. Soc.*, LXVIII (1912), 164–78, Pl. 10, and especially Fig. 3.

Attenuation of under limb of anticline after underturning.—There are still other consequences of the rapid loss of competence of an anticline after underturning has begun. The active force of compression, now no longer deflected upward into the first anticline but transmitted along its original direction, tends to reduce the volume of the included arches of inferior strata. The resistance which they offer to this reduction of volume tends to extend (stretch) the under limb (Fig. 22). It is a very general observation that thinning of the under limb is characteristic of so-called "overturned" anticlines, and emphasis may here be laid upon the point that, were anticlines really overturned, as has been so generally supposed, it is the upper limb which should be attenuated by the process, and not the lower (Fig. 23).[1]

FIG. 22.—Stretched under limb of a recumbent anticline. Drawn from a photograph of the Dent de Morcles as seen from Les Martinets, western Switzerland.

Though closed anticlines with attenuated upper limbs have, so far as known, never been observed in folded rock formations, they are, on the other hand, the characteristic type of close recumbent folds in the ice of glacier snouts, where the action of gravity and the resistance of friction in the lower layers force the upper layers to override the lower in true overturning movements (Fig. 24, p. 182).[2]

FIG. 23.—Attenuated upper limb of an anticline, a necessary consequence of overturning.

Not only may the lower limb of underturned anticlines be attenuated by stretching due to the resistance of the inclosed inferior strata, but the upper limb may in this stage be bulged upward as a result of the same system of forces.

[1] See also *ante*, p. 82, and Fig. 7. The sinking of the crown in an anticline tends to develop a tension within the upper limb, and it is perhaps conceivable that this tendency might in some stage either equal or overbalance that which normally causes attenuation of the lower limb, yet so far as known no example is furnished by folded strata.

[2] See among other views which show this effect: *Med. om. Gronland*, XLVI (1912), Fig. 24; *The Alpine Journal*, London, XXI, 187; Chamberlin and Salisbury, *Geology* I, 280, Fig. 268.

Possible formation of a magma macula beneath an anticline.—From examination of Fig. 17 and Table I (pp. 178 and 175) it will be seen that a relatively competent member near the top of a series of beds may remove from underlying members as much as one-half of the load which rests upon the arch. Under such conditions the underlying beds may be deformed by failure, even though the competent member is not (Fig. 25), and if at a depth where the isogeotherms are sufficiently high to melt the inferior members when thus partially relieved of load, a macula of magma may develop from the fused sediments. Such fusion is the more likely to occur

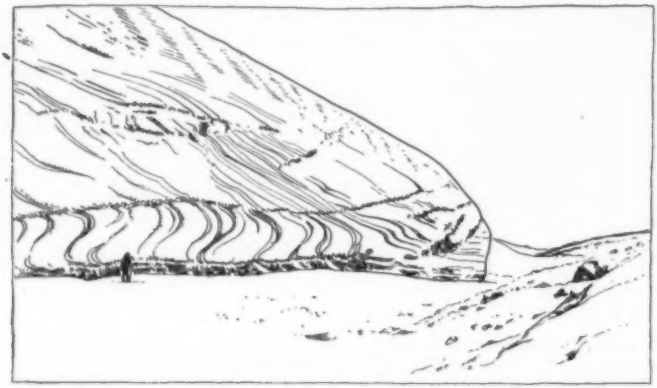
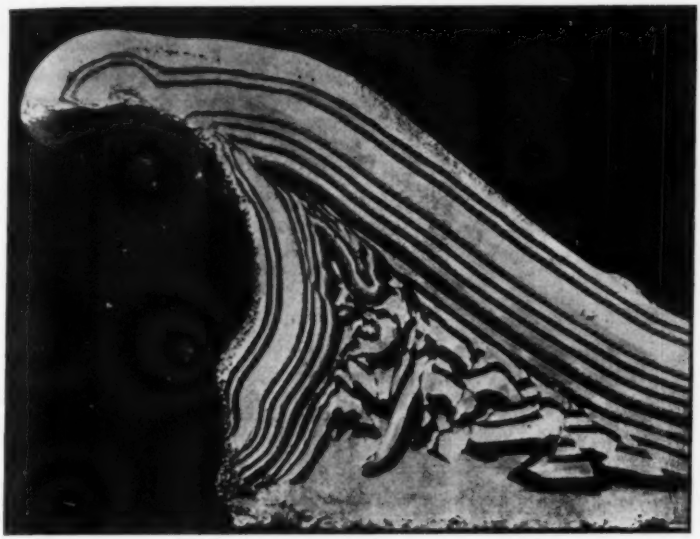


FIG. 24.—View of the front of the ice in northeast Greenland where overturned anticlines with thinned upper limbs are to be seen (after Koch and Wegener).

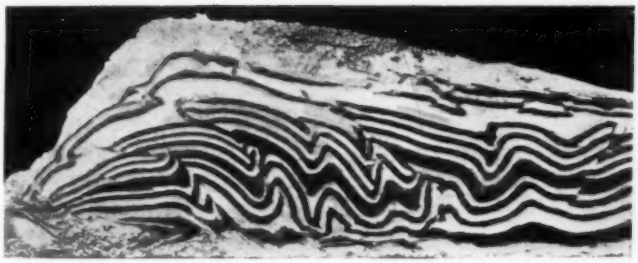
the lower the fusion interval of these inferior formations. The writer has elsewhere shown that the composition of igneous rocks in general is such that magma must inevitably develop, if at all, from the pelitic sediments, like shale and slate; the great abundance of which, no less than their structural weakness and their normal position in sedimentary series, is in favor of the view.[1]

Reduction of volume of anticline an efficient cause of elevation of magma.—Before the formation of a macula of magma through fusion

[1] "Some Considerations Concerning the Place and the Origin of Magma Maculae," *Gerland's Beiträge zur Geophysik*, XII (1913), 329–61, Figs. 1–8; see also "Variations in Composition of Pelitic Sediments in Relation to Magmatic Differentiation," *Comptes rendus 12me Congrès Géologique International*, Canada, 1913.



A



B

FIG. 25.—Results of lateral compression of parallel horizontal layers of materials which have varying degrees of rigidity, but are rendered plastic by the loads upon them. The active force is applied at the left (after experiments by Bailey Willis).

A, relatively less rigid beds deformed by failure beneath a competent (more rigid) stratum. There is also to be observed a slide which passes through all members alike.

B, successive anticlines and slides—imbricated structure.

of the roll of sediments beneath a relatively competent member, these inferior sediments support, as we have seen, a considerable portion of the entire superincumbent load. After fusion this support to the competent arch, which has hitherto been in excess of half the load, is now replaced by the molten magma of high incompressibility and perhaps also high viscosity. The compressive stress is now exerted through the under limb of the anticline in such a way as to squeeze or compress the macula. Under this action the under limb may suffer greater or less extension and consequent attenuation, but there must also be a tendency for the mass of magma to find an outlet along the path of least resistance, and it may in consequence fuse a course for itself upward toward the earth's surface (Fig. 26). In the upper levels any fractures that

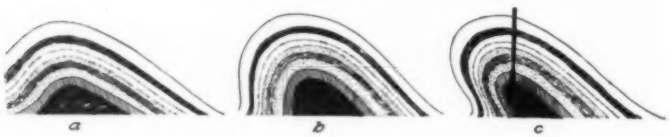


FIG. 26.—Diagrams to illustrate the tendency to reduction in the volume of progressively underturned anticlines and a consequent cause of the elevation of lava toward the earth's surface.

may exist are likely to be followed, and more especially fracture intersections. Recent studies make clear that magmas have the capacity of melting their own way by the process of overhead stoping. If such magma arrives at the surface along essentially vertical paths, its loci of emergence will constitute a series of arcs parallel to, and generally behind, the folded mountain arcs beneath which the maculae were developed. Thus we encounter in a consideration of the mechanics of folded mountain arcs a possible explanation of the position of volcanic arcs, and a possible solution of the vexed problem of the cause of elevation of magma in volcanoes of markedly Pacific type.

Volcanic vents once secured at the surface, magma should be exuded or ejected, and partial and further temporary relief be secured below from the compressive stress. Broad relationships

—rather than close responses— should therefore be expected to connect the growth of mountains and their attendant seismic disturbances with volcanic manifestations. The variations in the competence of the rising arch particularly after underturning has begun, considered in connection with the incidents of failure and their attendant consequences (hereafter to be discussed), are such as to make probable long-period variations particularly, both in seismic disturbance and in volcanic extravasation.

Backfolding of anticlines.—As yet comparatively little attention has been given by geologists to the effect of the local occurrence of weak or strong facies of a formation or series upon the character of the folds produced in them.[1] The subject is too complex and too little known to be discussed at length, but there are yet some

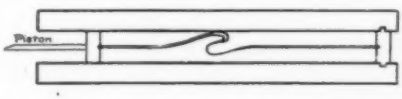


FIG. 27.—Backfold induced in a leaden strip above a local zone of weakness (after Daubrée's experiment).

very significant indications of its importance in fixing the location of the rare backfolds which have sometimes been described. In this connection a simple experiment by Daubrée is illuminating.[2] The strip of lead, which in so many of his tests was compressed from the end by a piston, was in one case locally weakened by thinning at some distance from the piston head, and the amplitude of upward deflection was limited by a horizontal beam above. The flexible strip was under these conditions deformed into a true backfold (Fig. 27), although it failed to simulate the Glarus double-fold as had been intended.

Nature has furnished an even better illustration in the Weissenstein of the Chain Jura, which the series of parallel profiles by

[1] Paulcke's experiments fail to afford altogether satisfactory results for the reason that his competent member is insufficiently loaded and does not fold.

[2] *Op. cit.*, p. 296, Fig. 85.

Buxtorf displays to the best possible advantage.[1] In these profiles (Fig. 28) the western (lower) ones reveal a slightly underturned anticline with perhaps some late bulging-upward of the upper limb,

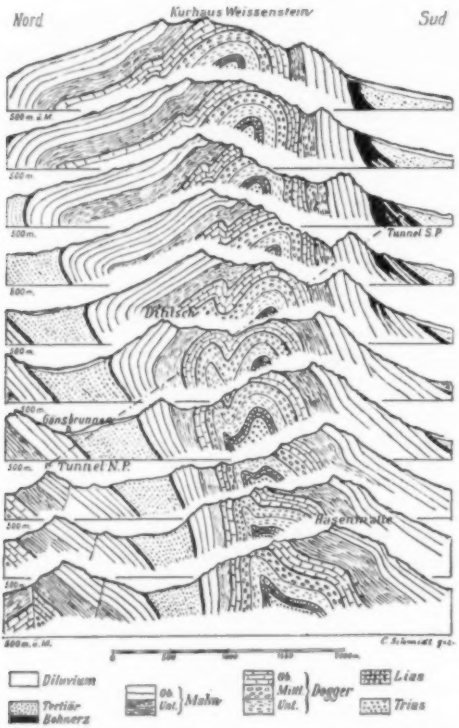


FIG. 28.—Series of geological profiles through the Weissenstein, Chain Jura, showing the development of a backfold above the *Bohnerzformation*, which is represented in black (after Buxtorf).

but with no indication of backfolding. Farther to the eastward, however, where a thin zone of the *Bohnerz formation* in part replaces

[1] Aug. Buxtorf, "Geologische Beschreibung des Weissensteintunnels und seine Umgebung," *Beitr. z. Geol. Karte d. Schweiz*, N.F., XXI (1907); C. Schmidt, A. Buxtorf, und H. Preiswerk, *Führer zu den Exkursionen der deutsch. geolog. Gesellschaft im südl. Schwarzwald, im Jura und in den Alpen*, 1907, pp. 21–22.

the strong Malm of the competent arch, the anticline is backfolded and in a degree dependent upon the thickness of the weaker formation.

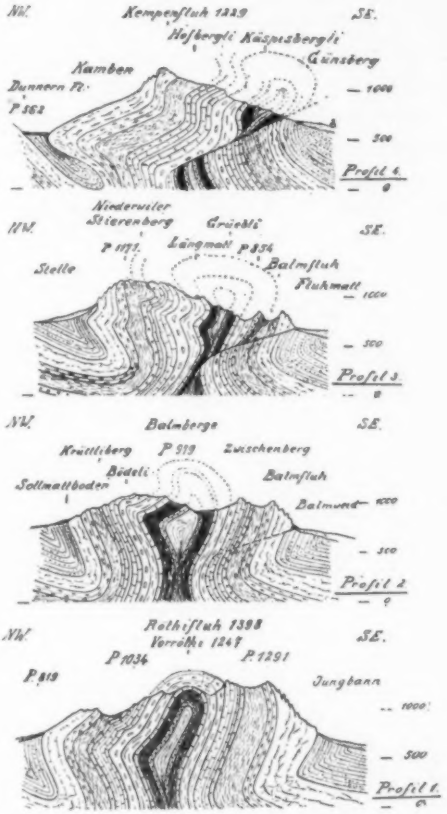


FIG. 29.—Backfolding due to the presence of a disjunctive surface in the folding formations. Series of profiles through the Weissenstein, Chain Jura (after Buxtorf).

The same district of the Weissenstein folds has supplied an equally instructive example of backfolding (near Balmberg-Günsberg), but one where the determining local weakness was a plane of fracture and not a zone of weak rock (Fig. 29).

Fan (carinate) anticlines may thus be a result of backfolding, though they may possibly in other cases be due to compression under the action of equal thrusts from opposite directions. It is, on the other hand, extremely difficult to conceive of conditions which could give rise to a fan or carinate syncline, for the reason that synclines, like anticlines, should develop above the zone of maximum pinch (see Fig. 19, p. 179). It is thus with a certain satisfaction that we may contemplate the abandonment of the conception of the Glarus double-fold, which in an earlier generation was standard doctrine in tectonics and required us to account for supposed fan synclines upon a gigantic scale (see *ante*, Fig. 1, p. 76).

Petrological Abstracts and Reviews

Edited by ALBERT JOHANNSEN

Allen, E. T., and Crenshaw, J. L. "The Mineral Sulphides of Iron. With Crystallographic Study by Esper S. Larsen," *Amer. Jour. Sci.*, XXXIII (1912), 169–236.

Allen, E. T., and Crenshaw, J. L. "The Sulphides of Zinc, Cadmium, and Mercury; Their Crystalline Forms and Genetic Conditions. Microscopic Study by H. E. Merwin," *Amer. Jour. Sci.*, XXXIV (1912), 341–96.

Arsandaux, H. "Sur la présence au Gabon de roches appartenantes à la série de la charnockite," *Comptes rendus de l'Acad. d. Sci., Paris*, CLIV (1912), 896.

In the Como Basin, a part of the French Congo, the author finds hypersthene granites, of a type hitherto found in but few localities, associated with ordinary granites and with amphibolite schists, gabbros, and diabases. Similar rocks of the charnockite family have been found on the Ivory Coast, about 1,000 miles northwest, but in that region the rocks found associated in the Como Basin characterize separate localities.

F. C. Calkins

Arschinow, W. W. *Ueber zwei Feldspäthe aus dem Ural.* Moskau, 1911. Pp. 12.

An article in the Russian language, with a German résumé, describing a potash-soda feldspar from the Ilmen, and an oligoclase-albite from the South Urals.

Arschinow, W. W. *Zur Geologie der Halbinsel Krym.*, Moskau, 1910. Pp. 16.

An article in the Russian language, with a German résumé, describing a basalt tuff from the neighborhood of Balaklava. The rock consists of a basic feldspar, of which an analysis is given, diopside, green hornblende, magnetite, and rarely brown basaltic hornblende. The cementing

material is in part amorphous, in part of fine crystal particles. Secondary minerals are calcite, zeolites, biotite, chlorite, and glauconite. The presence of glauconite, foraminifera, radiolarians, and sponge spicules, and the gradual transition of the tuff to other sedimentary rocks, indicate a submarine origin. A. J.

BOEKE, H. E. "Räumliche ternäre Kristallisationsmodelle für den Unterricht in physikalisch-chemischer Mineralogie," *Centralbl. f. Min., etc.*, 1912, 257–69.

BOEKE, H. E. "Karbonschmelzen unter Kohlensäuredruck. II. Ueber Witherit, Alstonit, Barytokalzit und Strontianit," *Mitth. d. Naturforsch. Gesell. Halle*, III (1913). Pp. 12.

BOEKE, H. E. "Mineral- und Gesteinsbildung aus dem Schmelzfluss (Magma) und durch Pneumatolyse," *Handwörterbuch der Naturwissenschaften*, VI (1912), 919–30.

A general paper on the formation of minerals and rocks from a magma.

BOEKE, H. E. "Die Schmelzerscheinungen und die umkehrbare Umwandlung des Calciumcarbonats," *Neues Jahrb.*, 1912 (I), 91–121.

An apparatus is described for producing temperatures up to 1600° and under pressures to 150 atmospheres. Iceland spar was found to melt, without decomposition, under a pressure of at least 110 atmospheres of CO_2, at 1289°. Mixed melts of calcium carbonate and calcium oxide were found to crystallize as a eutectic of 91 parts by weight of $CaCO_3$ and 9 parts of CaO at 1218°, and without the formation of crystals of intermediate composition. At $970 \pm 5°$ calcium carbonate reaches its inversion point; below this calcite is the stable form. A. J.

BOEKE, H. E. "Ueber die graphische Ermittelung der Krystallelemente und den Zonenverband in der gnomonischen Projection," *Zeitschr. f. Kryst.*, LII (1913), 175–78.

BOWEN, N. L. "The Melting Phenomena of the Plagioclase Feldspars," *Amer. Jour. Sci.*, XXXV (1913), 577–99.

BÜCKING, H. "Die Basalte und Phonolithe der Rhön, ihre Verbreitung und ihre chemische Zusammensetzung," *Sitzb. Akad. Wiss. Berlin.* XXIV (1910), 490–519.

The rocks described are feldspar basalts, nephelite basalts, nephelite basanites, nephelite tephrites, hornblende basalts, basaltites (trachydolerites), limburgites, and phonolites. Analyses are given of 78 rocks and 22 mineral constituents. There is a 2-page bibliography.

A. J.

BÜCKING, H. "Ueber vor- und nachbasaltische Dislokationen und die vorbasaltische Landoberfläche in der Rhön," *Zeitschr. d. deutsch. geol. Gesell.*, LXIV (1912), 109–24.

CRAWFORD, R. D. *Geology and Ore Deposits of the Monarch and Tomichi Districts, Colorado. Bull. 4*, Colo. Geol. Survey, Boulder, 1913. Pp. 317, pl. 25, figs. 15.

While a great part of this report is economic, there are some 87 pages devoted to the igneous rocks of the region, 21 to sedimentary rocks, and 17 to the processes of intrusion, metamorphism, etc. The pre-Cambrian rocks described are granitic gneiss, hornblende gneiss, hornblende schist, mica schist, garnetiferous schist, biotite-sillimanite schist, quartzite, granite, granite porphyry, syenite, hornblendite, and diorite. Post-Carboniferous igneous rocks are quartz diorite, quartz monzonite gneiss, quartz monzonite, granite, quartz monzonite porphyry, andesite, quartz latite, monzonite porphyry, latite, latite porphyry, andesite porphyry, rhyolite, rhyolite porphyry, pitchstone porphyry, and breccias.

A. J.

DALE, T. NELSON, and GREGORY, HERBERT R. *The Granites of Connecticut.* Bull. 484, U.S.G.S., Washington, 1911. Pp. 137, pl. 7, figs. 12.

This bulletin is a companion volume to those on the granites of Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont (Bulls. 313, 354, 404, U.S.G.S.). The granites of the state (the term granite being here made to do service for granites, monzonites, diorites, pegmatites, and gneisses) are very varied in character, ranging in texture from coarse pegmatites to fine quartz monzonites and from equigranular to porphyritic. In color they range from blue-black to light gray and

pinkish red. The rocks have been used for building purposes, monuments, bridges, curbing, paving blocks, and road metal; the amount of production in the last ten years averaging $500,000 a year.

A. J.

DALE, T. NELSON. *Supplementary Notes on the Commercial Granites of Massachusetts.* Bull. 470-G, U.S.G.S., 1911. Pp. 6–56.

Supplementary to Bulletin 354, previously reviewed.

DALE, T. NELSON. *The Commercial Marbles of Western Vermont.* Bull. 521, U.S.G.S., 1912. Pp. 170, pl. 17, figs. 25.

In this bulletin, Professor Dale has described the western Vermont marbles in much the same manner as he did the granites in a number of earlier bulletins. After a preliminary description of marbles in general, covering 60 pages and including a 6-page bibliography, the various marble quarries of the area under consideration are described in detail. Professor Dale's bulletins on the building and ornamental stones are greatly appreciated, and it is to be hoped that he will continue issuing them. Similar bulletins from other parts of the country would be of considerable value.

A. J.